APPROACH ROADS GREENLAND 1956-1957 PROGRAM

TECHNICAL REPORT NO. 3-505

Report 2

April 1963

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
CORPS OF ENGINEERS
OFFICE OF THE DIRECTOR
VICKSBURG, MISSISSIPPI

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11 September 1962

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TO: Director, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Technical Report 3-505, Report 2, "Approach Roads, Greenland 1956-1957 Program," dated April 1963 is approved for publication and distributior according to List A.

FOR THE COMMANDER:

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ROBERT F. JACKSON
Acting Chief, Earth Sciences Sect
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APPROACH ROADS
GREENLAND 1956-1957 PROGRAM

TECHNICAL REPORT NO. 3-505

Report 2

April 1963

Prepared by

Arctic Construction and Frost Effects Laboratory
U. S. Army Engineer Division, New England

for

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

PREFACE

Primary responsibility for Project 1, Approach Roads, *Greenland Research and Development Program*, was assigned by the Office, Chief of Engineers, to the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. Prior to 1955 responsibility for the project had been assigned to U. S. Army Engineer Research and Development Laboratory, Fort Belvoir, Va. In a letter dated 18 March 1955 WES requested the U. S. Army Arctic Construction and Frost Effects Laboratory (ACFEL)* to assume the work of planning and conducting the investigation, including preparation of progress reports and a final report; ACFEL accepted the work in a 1st indorsement dated 31 March 1955.

This report is the third progress report on the subject. The first was prepared by ACFEL for the U. S. Army Engineer Research and Development Laboratories and covered the investigations conducted in 1954. The second report was prepared by ACFEL in cooperation with WES and covered the investigations conducted in 1955. This report, prepared by ACFEL in cooperation with WES, covers the work accomplished in 1956 and 1957.

Mr. H. W. Stevens, Chief, Greenland Research and Development Projects, ACFEL, was designated supervisor for the investigation. He organized the project, supervised the fieldwork, and prepared the reports. Dr. Ronald F. Scott was Field Project Engineer in 1956, and Mr. Frederick J. Sanger was Field Project Engineer in 1957. The investigation was carried out under the direction of Mr. Kenneth A. Linell, Chief, ACFEL.

WES reviewed and approved the plan of test, provided support throughout the entire project by furnishing personnel and equipment, and reviewed the reports. Mr. W. J. Turnbull, Chief of the Soils Division, following an inspection of the road in 1955, made several pertinent suggestions which were adopted in the 1956-1957 program, and has maintained a continuous personal interest in this project. WES assigned Mr. William R. Beckett as Assistant Project Engineer in 1956. Mr. A. J. Green held the same position in 1957. Messrs. S. J. Knight and A. A. Rula of the Army Mobility Research Center represented WES and worked closely with ACFEL during all phases of the project.

Mr. C. R. Foster, formerly Chief, Flexible Pavement Branch, WES, and Dr. Mikael J. Hvorslev, Consulting Engineer, WES, inspected the fieldwork in 1956 and 1957 and contributed very valuable comments and suggestions. Mr. Thomas B. Goode, Chief, Field Explorations Branch, WES, was consultant for core-drilling operations in the frozen ground and ice in 1956 and 1957.

Col. A. P. Rollins, Jr., CE, Col. E. H. Lang, CE, and Col. A. G. Sutton, Jr., CE, were Directors of the Waterways Experiment Station during the field work and preparation and publication of this report. Mr. J. B. Tiffany was Technical Director.

Excellent cooperation was received from Lt. Col. Elmer F. Clark and the officers and enlisted men of the U. S. Army Engineer Arctic Task Force. This cooperation contributed substantially to the success of the investigation.

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* Now the U. S. Army Cold Regions Research and Engineering Laboratory of the Army Materiel Command Hq, Environmental Research.

SUMMARY

This report presents the results of investigations (begun in 1954) conducted during the summers of 1956 and 1957 at the edge of the Greenland Ice Cap. It is a progress report on the development of methods, techniques, and criteria for constructing roads on both glacial ice surfaces and adjacent ice-free terrain.

Detailed descriptions of the terrain and weather are given, and other pertinent factors that define conditions under which the criteria developed for road construction and maintenance may be applied are presented. Ice movement, ice ablation, meltwater flow, performance and durability of road fills, subsurface temperatures, and characteristics of thaw penetration were studied. Measurements were made by surveying, soil testing, and reading of instruments.

A study was made of the soil properties and physiography of an area 10 to 15 miles square in the vicinity of Camp TUTO to obtain (a) a knowledge of the soils available for use as borrow materials and (b) data necessary for the design of roads, building foundations, and other facilities. In addition detailed measurements were made of surface soil properties to complete the information that, together with meteorological data, was required for making computations to predict rate and depth of thaw.

Road construction in 1956 and 1957 was primarily a continuation of the road construction begun in 1955 to make existing roads more useful from an operational standpoint and to construct new roads to satisfy investigational requirements.

In 1956 an 80-ft-long, wooden-pile-bent bridge was constructed on the ice by six men in 2-1/2 weeks. The bridge supported the heaviest (29 tons) mobile equipment at the site and performed satisfactorily for 1-1/2 thaw seasons with a minimum of maintenance.

It is recommended that certain phases of the investigations be continued to further develop methods, techniques, and design criteria for construction of roads on ice and frozen ground.

Appendix A presents the detailed Plans of Tests for 1956 and 1957; Appendix B comprises tables and charts giving the number of personnel and types of equipment used in the project, miscellaneous weather data, logs of borings, and results of ice surface measurements. Appendix C is a report by Mr. Stanley D. Wilson on the use of the Wilson Slope Indicator at TUTO.

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DEFINITIONS

Ablation	The process of removing snow or ice from a glacier or snowfield by melting and evaporation.
Active zone	The top layer of ground subject to annual freezing-and-thawing.
Average annual temperature	The average of the average daily temperatures for one year.
Average daily temperature	The average of the maximum and minimum temperatures for one day, or the average of several temperature readings taken at equal time intervals during one day, generally hourly.
Berm	A blanket of soil, approximately 1 ft thick, spread over the ice surface, connected to the toe of fill of the road.
Degree-days	The degree-days for any one day equals the difference between the average daily air temperature and 32 F. The degree-days are minus when the average daily temperature is below 32 F (freezing degree-days) and plus when above (thawing degree-days).
Dirt band	A layer of debris (rocks, soil) in firn or ice.
Firn line	The lower occurrences of firn (snow at least one summer old) on a glacier; also "firn limit."
Frost action	A general term for freezing-and-thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.
Frost heave	The raising of a surface due to the formation of ice in the underlying soil.
Frost-susceptibility	The property by which ice segregation occurs in a soil when the requisite moisture and freezing conditions are present.
Ice crack	A narrow opening in the ice resulting from differential ice movement.
Ice hummock	A mound or hillock caused by an upward pressure within the ice and/or by differential melting.
Ice lens	A discontinuous layer of ground ice tapering at its extremities.
Ice movement	The motion that exists within the ice of a glacier or ice sheet; also "glacier flow."
Mean annual temperature	The average of the average annual temperatures for several years.
Micrometeorology	The detailed study of the physics of the zone close to and just beneath the earth's surface.
Patterned ground	A general term describing ground patterns resulting from frost action such as soil polygons, stone circles, stone stripes, and solifluction stripes.

DEFINITIONS (Continued)

Permafrost	Perennially frozen ground.
Permafrost table	An irregular surface that represents the upper limit of permafrost.
Thawing index	The number of degree-days between the lowest and highest points on the cumulative degree-days-time curve for one thaw season. It is used as a measure of the combined duration and magnitude of above-freezing temperatures occurring during any given thawing season. The index determined for air temperatures at 4.5 ft above the ground is commonly designated as the air thawing index, and that determined for temperatures immediately below a surface is known as the surface thawing index.
Thaw line	An irregular surface that represents the lower limit of thaw.
Thaw season	That period of time during which the average daily temperature is generally above 32 F.
Thaw weakening	The reduction in strength and load-supporting capacity, during thaw periods, of a frost-susceptible soil in which ice segregation has occurred.
Thermal regime	The temperature pattern existing in a body.

REFERENCES

Air University, Research Studies Institute, Arctic, Desert, Tropic Information Center, *Glossary of Arctic and Subarctic Terms*. ADTIC Publication A-105, Maxwell Air Force Base, Ala., September 1955.

U. S. Army, Office, Chief of Engineers, *Arctic and Sub-arctic Construction – General Provisions* (formerly *Engineering Manual for Military Construction*, Part XV, Chapter 1). EM 1110-345-370, October 1954.

APPROACH ROADS, GREENLAND 1956-1957 PROGRAM

I. INTRODUCTION

Purpose

1. The studies described herein are a continuation of work commenced in calendar year 1954. The objective of this work was to develop methods, techniques, and design criteria for the construction and maintenance of roads on both glacial ice surfaces and adjacent ice-free terrain under conditions such as those typified by the TUTO area near Thule Air Force Base, Greenland. Detailed Plans of Tests for 1956 and 1957 are included as Appendix A.

The investigations were conducted at Camp TUTO which is located 14 miles from Thule Air Base, near the edge of the Greenland Ice Cap (see Fig. 1). The camp was operated by the U. S. Army Engineer Arctic Task Force (EATF), a military group organized to support research and development activities by the Department of the Army. Figure 2 is a detailed map of the area where project activities took place, and it shows all facilities constructed as part of the project program as well as the location of test pits, survey points, reference points, and other pertinent positions. The map was prepared from data obtained during the original surveys that were completed as part of the project program. Location of installations and position of the ice edge will undoubtedly change with time as a result of new construction and retreat of the ice.

Scope

2. This report summarizes the work completed in 1956 and 1957, but inasmuch as 4 years had been expended on this investigation by the end of 1957, data are used from all 4 years of investigations and frequent reference is made to the interim reports of 1954 and 1955.[5,6*] However, some of the phases require more detailed investigation and/or observations, and at least 1 year more of fieldwork is recommended. This is, therefore, a progress report.

This report contains detailed descriptions of the terrain and weather, and presents other pertinent factors that define the conditions under which the criteria developed for road construction and maintenance may be applied. Criteria, methods, and techniques for road design, construction, and maintenance are presented, together with recommendations for further investigations.

II. PROJECT ORGANIZATION AND EQUIPMENT

3. Complex investigations conducted in remote regions, such as Camp TUTO in Greenland, require careful planning and organization of personnel, equipment, instrumentation, and logistics. Accordingly, the organization of the 1956-1957 project is described to aid in future similar investigations. A noteworthy feature of this investigation, and of other investigations in the Greenland Ice Cap Research Program of the Corps of Engineers, has been the cooperation that existed between the various Government agencies, and between the civilian and military personnel working side by side on the same project. This close cooperation was essential to the success of this and all other projects in the program.

1956 personnel

4. As in other years, supervision, testing, data recording, and all technical or specialized functions were performed by civilian employees of the U. S. Army Arctic Construction and Frost Effects

* Raised numbers refer to similarly numbered items in the list of references at the end of the report.

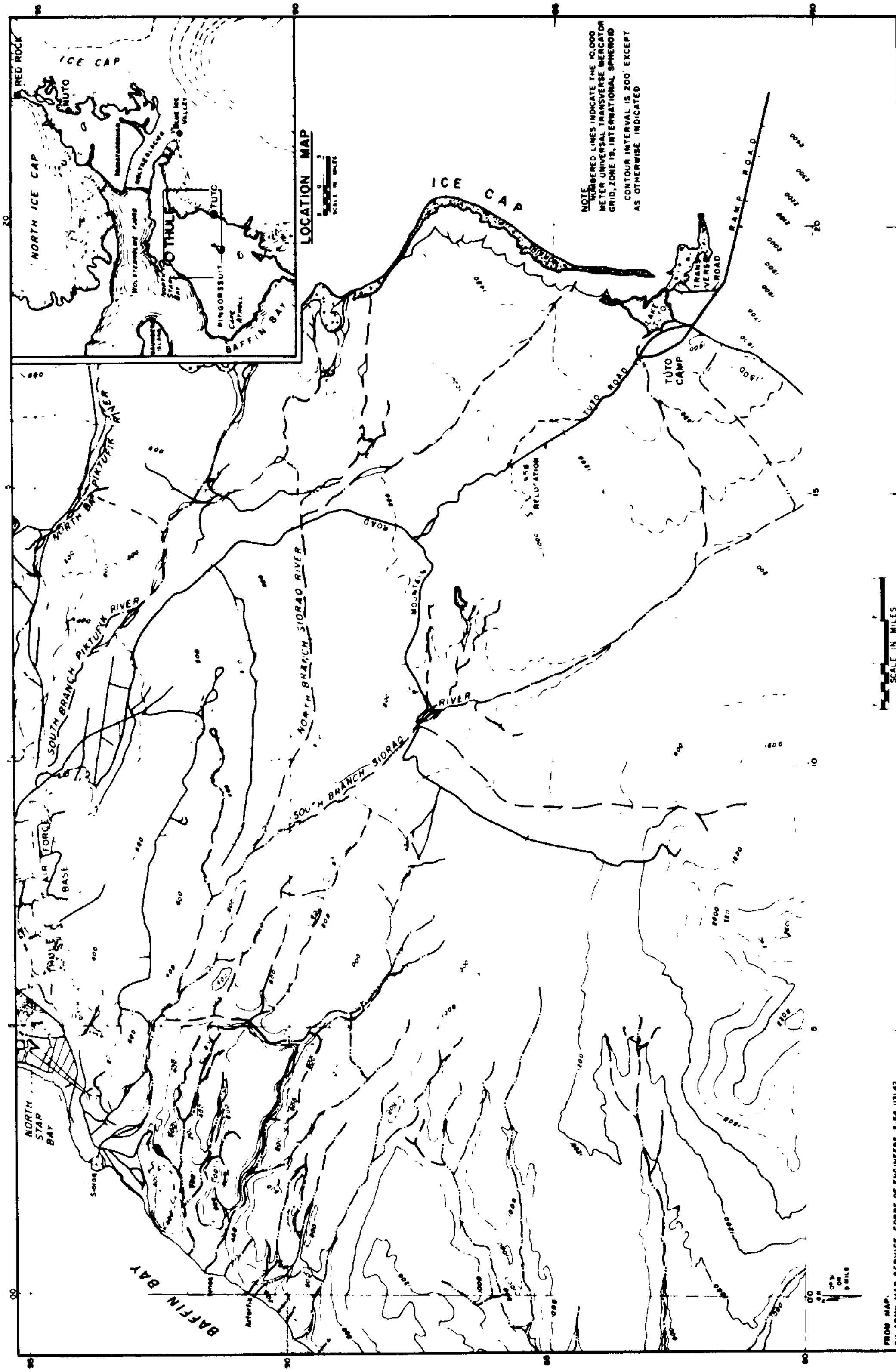


Figure 1. Map of Thule-TUTO area.

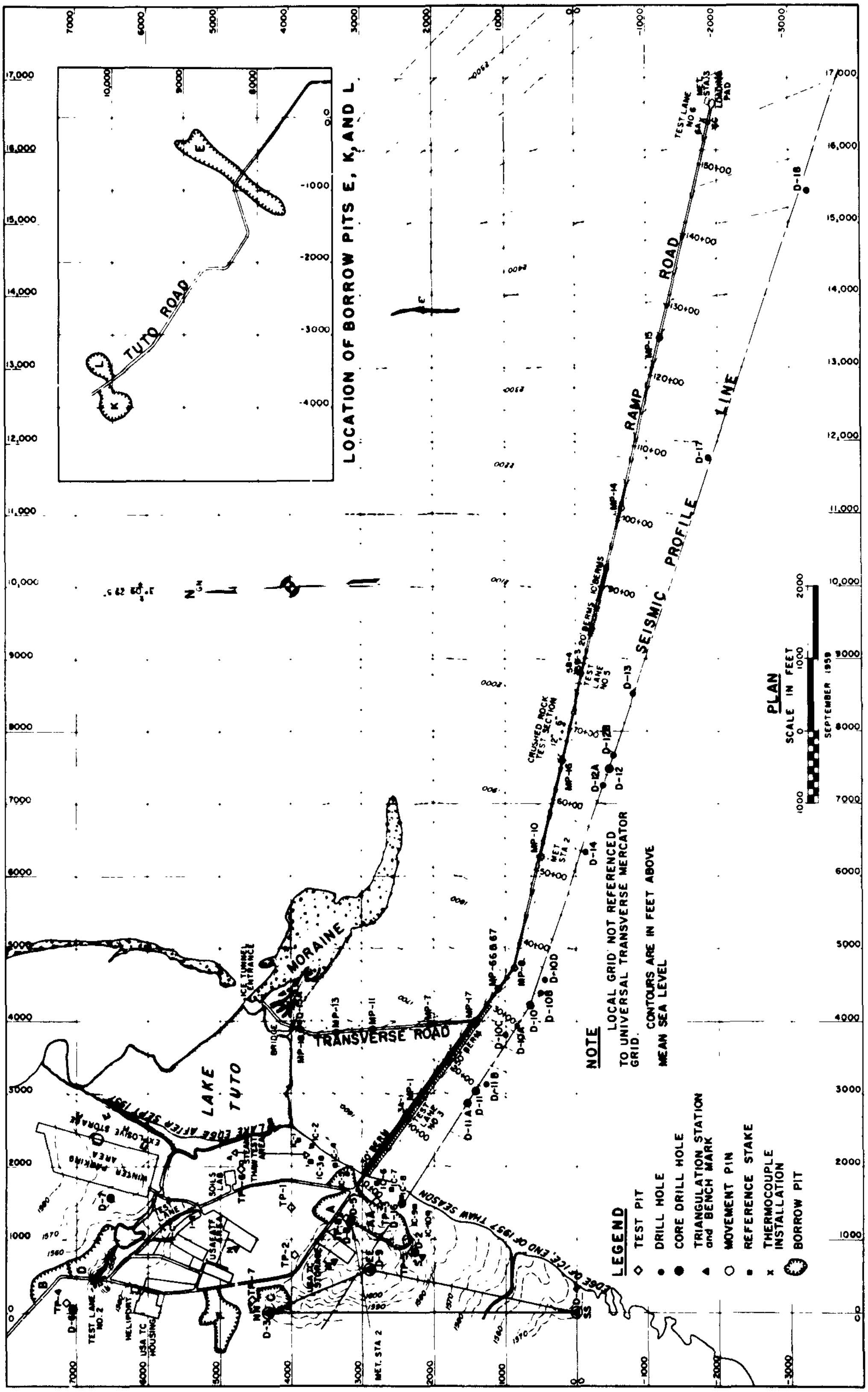


Figure 2. Camp TUTO and TUTO Ramp.

Laboratory (ACFEL) and the U. S. Army Engineer Waterways Experiment Station (WES). Construction, maintenance of construction equipment, and maintenance of living facilities at the worksite were performed by military personnel of the EATF. A complete list of personnel is given in Appendix B, Table B-I.

Civilian. Civilian personnel were responsible for measuring ice movement, ice ablation, melt-water flow, performance and durability of road fills, subsurface temperatures, and characteristics of thaw penetration; the measurements were obtained by surveying, soil testing, and reading of instruments. Since this type of work has increased from year to year, the civilian staff was increased over that of previous years by additional surveying and engineering aide personnel. Eight civilians were in the field from 4 June to 2 September 1956. This staff provided adequate supervision, technical knowledge, and skills, but they would have been unable to complete the entire program if military personnel from EATF had not helped them. The education and experience backgrounds of several of the military personnel were similar to those of civilian project personnel; therefore, similar tasks were assigned. It is estimated that the civilian staff expended 8820 man-hours in completing the summer's fieldwork.

Military. The foremen and heavy-equipment operators who constructed the gravel roads were military personnel of EATF (see Table B-I, Appendix B). These men, under the supervision of the Project Engineer, the Construction Supervisor, and noncommissioned officer foremen, operated all the equipment used to construct the roads. In addition, a small group from the Meteorological Branch, U. S. Army Signal Corps, was attached to Project 1. This group, consisting of one officer and three enlisted men, was responsible for the meteorological measurement program.

Adequacy of personnel. In general, the number and quality of the personnel were adequate. Incomplete phases of the summer's work are not attributable to personnel deficiency or incompetence, except that the meteorological data were not complete owing to the small size of the meteorological group.

1956 construction equipment

5. Two years' experience provided guidance on the most efficient type of construction equipment for the job. The selection of type and number of pieces of equipment was based on experience and the amount of work contemplated for each construction season. EATF provided practically all the equipment requested; moreover, the items were in good repair, many of them new. Therefore, the analysis of work output for 1956 is more significant than that for other years; it shows the output which can be obtained in the TUTO environment with a normal quota of equipment and with normal maintenance and repair.

Equipment. Table I lists the equipment used, the general use to which it was put, and the percentage of total work time required for maintenance. Repair time was generally greater than it would be for similar construction in the temperate zone. Under the rigorous climatic and terrain conditions at TUTO, above-average breakdown of equipment should be expected. The inevitable (in remote areas) shortage of spare parts and inadequate repair shops and tools contribute to the increased repair time.

One item of equipment used in 1956 warrants some discussion. It had been reported[6] that scrapers were useless in the TUTO area because of the bouldery nature of the borrow. Yet, considerable use was made of a scraper in 1956. It was desired that the construction of road and berms progress simultaneously, but there were insufficient bulldozers, shovels, and trucks to borrow coarse, fine, and random material at the same time. When borrowed materials were stockpiled for a scraper by a bulldozer, the scraper could load itself and make significant progress in constructing berms, loading, and spreading. A scraper was employed for some time to construct berms, although the work could have been accomplished more efficiently with dump trucks.

The standard-type equipment used was generally satisfactory. Because of the extremely rough

Table I. Construction Equipment Performance, 1956

Item	Quantity of Item	Use	Hours Worked	Hours Deadlined	% of Total Work Time Deadlined
Bulldozer (D-8)	6	Snowplowing, stockpiling, spreading, and compacting	2400	283	10.5
Truck, dump, 10-cu-yd	9	Transporting borrow	4041	465	10.3
Shovels, tractor-mounted					
2-cu-yd	1	Loading trucks	450	39	8.0
3/4-cu-yd	1	Loading trucks	371	88	19.2
Grader, road, motorized	1	Fine-grading gravel roads	394	126	24.2
Scraper, towed type, 12-cu-yd	1	Loading and spreading	312	167	34.8
Rock crusher, 25-cu-yd/hr	1	Providing crushed rock from boulders	No record	No record	

terrain and the necessity for operating over unimproved ground, large, heavy models are preferred to small, light types. Repair and maintenance make simple mechanical controls preferable; for example, a mechanical hoist is preferable to a hydraulic hoist for bulldozers.

Work output. Table II summarizes the work accomplished with the equipment available. This

Table II. Logistical Data for 1956 Road Construction

Construction Item	Quantity cu yd	Man-hours*	Equipment Hours**						Fuel, gal	
			D-8	Truck, Dump, 10-cu-yd Capacity	2-cu-yd Shovel	3/4-cu-yd Shovel	Grader	Scraper	Diesel	Gas
Coarse Fill										
Ramp Road	13,552	3,947	703	1,339	203				9,220	741
Transverse Road	9,375	2,399	486	923	141				4,023	315
Widen Transverse Rd	1,639	610	85	163	25				835	92
Loading platform	747	172	39	75	12				558	32
	25,313	7,128	1,313	2,500	381				14,636	1,180
Fine Fill										
Ramp Road	3,026	788	155	256		87	27	17	2,058	142
Transverse Road	1,426	388	75	123		40	13		888	81
Widen Transverse Rd	87	12	5	8		3	1	5	25	12
Loading platform	104	7	5	8		4	3		39	2
	4,643	1,195	240	395		134	44	22	3,010	237
Miscellaneous										
Haul and TUTO roads	5,326	2,135	278	328	18	140	41	36	3,127	881
Berms	10,707	3,239	556	785	51	27		254	8,434	624
Crushed rock (road surface and bridge)	240	64	13	33		70†	3		167	15
Road maintenance							306			
Total	46,229	13,761	2,400	4,041	450	371	394	312	29,374	2,937

* Includes operators, foremen, and supervisors. Does not include maintenance men, surveyors, or design engineers.

** Includes hours of operation. Does not include deadline time. See Table I for number of pieces of each type of equipment and deadline time.

† Includes time loading crusher, in addition to time loading trucks.

table can be used as a guide in estimating logistic requirements.

Assuming that the equipment listed in Table I is used (one 2-cu-yd shovel, one 3/4-cu-yd shovel, six bulldozers, nine 10-cu-yd trucks, and one grader), that the workday is 9-1/2 hours, and that the haul distance is 3 to 4 miles, work output in constructing roads on ice would be as follows:

a. 30,092 cu yd of coarse and fine material were actually placed in 2895 hours. Therefore, nine trucks could place approximately 94 cu yd per hour or 890 cu yd per 9-1/2-hour day.

b. Approximately 300 ft of gravel road (2-1/2 ft thick, 30 ft wide) can be constructed on the ice per 9-1/2-hour day.

c. The 2-cu-yd shovel can load 67 cu yd per hour or service about seven 10-cu-yd trucks when haul time is 50 minutes or more.

d. The 3/4-cu-yd shovel can load 35 cu yd per hour or service three and one-half 10-cu-yd trucks when haul time is 40 minutes or more.

The work output is generally less than that expected for construction in warmer climates. Cold, high winds, blowing snow, and whiteout conditions account for part of the slowdown. Also the coarse, bouldery material is difficult to handle, and borrowing only from the thin, thawed, surface layer means frequent moves to new areas and extra bulldozer work to stockpile material. Special care must be taken to prevent major breakdown of equipment as replacement is impossible. For example, if a serious mechanical failure had incapacitated the 2-cu-yd shovel, nearly all construction progress would have ceased for the remainder of the short work season. Although the quantity and quality of the equipment proved to be adequate for the job at hand, efficiency would have been increased somewhat if additional equipment, especially dump trucks, had been available as standbys.

1956 test equipment

6. In addition to the construction equipment, EATF furnished several other items of equipment required for special tests. The more specialized instruments and test equipment were provided by either WES or ACFEL (see Table B-II, Appendix B).

1957 personnel

7. Table B-III, Appendix B, lists the personnel who participated in Project 1 in 1957, including the military construction group and the military men of EATF who were assigned continuously to the project and who worked with the civilians. The military group of the Meteorological Branch, U. S. Army Signal Corps, who conducted the program of meteorological measurements, comprised an officer and 18 enlisted men. This group operated as an independent organization assigned to EATF.

The project staff was adequate, and no significant lack of skills, knowledge, or manpower was noted. Much credit is due both the civilian and military personnel for the responsible manner in which they performed their various jobs.

The military construction group operated the bulldozers, trucks, power shovels, graders, etc., used in constructing experimental roads and berms. This work required about 1 week. Two civilians and two Army enlisted men operated the drill rig used to drill holes in the ice for the installation of plastic tubes for inclinometer measurements. The number of personnel was adequate, and they accomplished the desired construction in an efficient manner.

1957 equipment

8. Equipment used by Project 1 was furnished by WES, ACFEL, and EATF. Equipment for the meteorological measurements was furnished by the U. S. Army Signal Corps, except for a sunshine

duration recording instrument which ACFEL furnished. The construction program for 1957 was limited to 1 week, and no evaluation of the efficiency of the heavy construction equipment was made. Observations were made of the feasibility of using certain specialized equipment for work on ice, including a drill rig with large-diameter augers and a trenching machine.

Equipment furnished by EATF. Construction equipment was furnished by EATF. As the 1957 program called for construction of only a few test roads involving about 1 weeks work, the construction equipment and operating personnel were under the supervision of Project 1 for this brief time only. For the remainder of the work season, the construction group was engaged in maintaining and/or improving roads, parking facilities, etc., under the direction of EATF. Project 1 personnel furnished advice and suggestions for this work as requested. Table B-IV, Appendix B, lists the construction equipment used during the Project 1 construction.

In addition to the heavy construction equipment, EATF furnished specialized equipment, as required, from standard Army issue. This equipment is also listed in Table B-IV.

All living quarters and facilities and all maintenance facilities were furnished by EATF.

Equipment furnished by WES and ACFEL. All specialized test equipment was furnished by WES or ACFEL (see Table B-IV). The largest item of this equipment was the drill rig and accessory equipment, which required special shipping arrangements. This item and a ditching machine comprised the two pieces of special equipment tested to determine their feasibility for future use.

Previously it had been noted that a machine capable of cutting channels in the ice would be useful. Thus in 1957 observations were made of the performance of a standard, crawler-mounted, ladder-type, ditching machine (Fig. 3). The machine was capable of cutting a trench 2 ft wide and

Figure 3. Ladder-type ditching machine used for cutting channels in ice (26 Aug 1957).

8 ft deep at a rate of 1 ft per minute. However, its maneuverability on the ice surface was poor due to its high center of gravity and narrow crawler treads. In principle the machine is considered excellent for this use, but it should be modified or redesigned by widening and lengthening the treads and

lowering the center of gravity. The cutting depth capacity could be reduced to 4 ft without decreasing the machine's usefulness.

The drill rig tested during the summer of 1957 was developed by the U. S. Army Engineer Research and Development Laboratories. It was an auger type, specially designed to handle large-diameter (up to 5 ft) augers. It was truck-mounted and had a 90-ft tower (Fig. 4). A test hole, 5 ft in diameter and 70 ft deep, was drilled in the ice at Mile 3 on the ice ramp. Rate of drilling was 1/4 ft per minute and no difficulties were encountered. This model of the drill obviously requires a stable, smooth surface to operate on, and therefore is not suitable for use on a rough, glacial ice surface. With a different mount (possibly skids or tractor), and an outrigger system for leveling and stabilizing, it would be practical for rapid drilling of large-diameter holes.

Figure 4. Rig used for drilling large-diameter holes in ice (26 Aug 1957).

Summary

9. *The 1956 program.* Eight civilians and four Army enlisted men supervised the work, conducted all tests, made all measurements, and to some extent took an active part in construction of facilities. In addition two civilians and two enlisted men operated a drill rig for 1 month to accomplish that phase of the work. A force of 27 Army enlisted men, including foremen and equipment operators, constructed all roads and other facilities required. This staff was adequate to accomplish the planned program.

One officer and three enlisted men of the U. S. Army Signal Corps set up and operated the meteorological station. This small staff was inadequate.

Road construction equipment included six D-8 bulldozers, nine 10-cu-yd dump trucks, one 3/4-cu-yd power shovel, one 2-cu-yd power shovel, one self-propelled grader, one scraper, and one rock crusher. Using this equipment, and with a haul distance of 3 to 4 miles, an average of 890 cu yd of gravel was placed (300 ft of gravel road, 2-1/2 ft thick and 30 ft wide) in a 9-1/2-hour day. The ratio of trucks to bulldozers and power shovels was approximately correct for the haul time (40 to 50 minutes). Additions to the number of trucks used would require corresponding additions to the number of bulldozers and power shovels.

Progress was impaired by (a) inclement weather, (b) the difficult, slow procedure necessary to obtain borrow materials, and (c) the lack of replacement equipment which made it necessary to take extraordinary precautions to prevent major breakdowns.

The 1957 program. Seven civilians and four Army enlisted men conducted the program in 1957. Two civilians and two Army enlisted men operated the drill rig used to drill holes in the ice for the installation of plastic tubes for inclinometer measurements. Seventeen military personnel worked 1 week to construct test road sections. One officer and 18 enlisted men of the Meteorological Branch of the U. S. Army Signal Corps set up and operated the meteorological stations. All personnel were carefully selected for personality and ability to accomplish the extensive program in the short working

time available; their efforts were responsible for the success of the year's work.

A standard, crawler-mounted, ladder-type, ditching machine was found to be efficient in cutting trenches in ice, but its maneuverability on the ice ramp was poor.

An experimental drill rig capable of handling large-diameter augers drilled a 5-ft-diameter hole, 70 ft deep, in ice. The present model (truck-mounted) is incapable of movement under its own power on the rough ice surface.

III. WEATHER

General

10. In 1954 and 1955, project personnel, in addition to their regular duties, made meteorological measurements using such instruments as were available in the laboratories of the cooperating agencies. Commencing in 1956, the meteorological program was conducted by a detachment from the Meteorological Branch, U. S. Army Signal Corps. The recorded data were transmitted to the National Weather Records Center, Asheville, N. C., which furnished tabulations of these data to interested agencies. The 1956 program was in accordance with requirements submitted by WES and ACFEL. In 1957, the program combined the requirements of several agencies including WES, ACFEL, SIPRE,* and the Climatic Research Laboratories of the U. S. Army Quartermaster Corps. WES and ACFEL had two objectives: (a) to obtain accurate and complete weather records for the work season; and (b) to provide micrometeorological data for use in the continuing study of relations involved in predicting depth and rate of thaw and refreezing. The latter studies and pertinent meteorological data are discussed in section VI of this report. In section III, the general weather characteristics of the area in 1956 and 1957 are summarized and discussed. Also, averages for 4 years (1954-1957) are given and discussed under "Analysis of TUTO Weather" and in the summary.

1956 weather

11. *Equipment.* Three weather stations were established and operated in 1956. Table III lists the location of each (see also Fig. 2), the measurements made, the equipment used, and the periods of record. It took approximately 2 months to erect the stations and set up the instruments because of the small number of personnel and their lack of experience in arctic operations. Also an unusually deep snow cover existed until the first week in July. The instrumentation was found to be too complex for the weather and terrain conditions. During the season, difficulty was encountered with power breakdowns, maladjustment of instruments, icing during storms, etc. However, a great deal of experience in the operation of meteorological instruments in the Arctic was gained, and useful data were accumulated.

Review of 1956 weather. Air temperatures, wind velocities, wind direction, cloud cover, and relative humidity are shown in Figures B1 and B2, Appendix B.

Air temperatures show that 1956 was a relatively cool summer (see references 5 and 6 for record of 1954 and 1955). At Camp TUTO (Station 1), thawing temperatures did not commence until 15 June, and freeze-up commenced 19 August. Average daily temperatures in July and August were in the mid-30's, but for a 2-day period in July the temperature dropped below freezing for part of each day.

The air temperature at Mile 1 (Station 2) on the ice cap was consistently 2 F lower than that

* Formerly U. S. Snow Ice and Permafrost Research Establishment, now U. S. Army Cold Regions Research and Engineering Laboratory.

Table III. 1956 Meteorological Stations and Equipment

Measurement	Instruments	Period of Record
	Station 1 **On Ground: 300 ft from Edge of the Ice Cap, El 1600 ft**	
Air temperature at 4 ft	Hygrothermograph in standard weather shelter	9 June-30 Aug
Air temperature at 4, 8, and 16 ft	Thermocouples in radiation shields with recording, multipoint potentiometer	14 June-31 Aug
Ground temperature at surface, -1/10, -4, -20 in.	Thermocouples with recording, multipoint potentiometer	13 June-31 Aug
Wind speed at 4, 8, and 16 ft	Anemometer, ML-80, with operations recorder	14 June-31 Aug
Wind direction at 4 ft	Wind vane, ML-79, observed at 6-hour intervals	15 June-30 Aug
Relative humidity at 4 ft	Hygrothermograph in standard weather shelter (checked by sling psychrometer at 6-hour intervals)	9 June-30 Aug
Barometric pressure at 4 ft	Aneroid barometer, ML-102, in standard weather shelter	15 June-30 Aug
Cloud cover	Observed at 6-hour intervals	15 June-30 Aug
Sunshine duration	Marvin-type, black-bulb meter with operations recorder	25 June-31 Aug
Solar radiation, total incoming, all wave	Gier-Dunkle-type, aspirated radiometer with recording, multipoint potentiometer	21 June-31 Aug
Solar radiation, net exchange, all wave	Gier-Dunkle-type, aspirated radiometer with recording, multipoint potentiometer	13 June-31 Aug
Solar radiation, total hemispherical short wave	Eppley-type pyrheliometer with recording, multipoint potentiometer	21 June-31 Aug
	Station 2 **On Ice: 1 Mile Out on the Ice Cap, El 1800 ft**	
Air temperature at 4 ft	Hygrothermograph in standard weather shelter	23 June-13 July 22 July-30 Aug
Wind speed at 4 ft	Observed at 6-hour intervals with hand-held anemometer, ML-433	25 June-30 Aug
Relative humidity at 4 ft	Hygrothermograph in standard weather shelter	23 June-31 Aug
Solar radiation, total incoming, all wave	Gier-Dunkle-type, aspirated radiometer with recording, multipoint potentiometer	2 July-14 July 1 Aug - 2 Aug 10 Aug -21 Aug
Solar radiation, net exchange, all wave, over snow or ice surface	Gier-Dunkle-type, aspirated radiometer with recording, multipoint potentiometer	27 June-14 July
Solar radiation, net exchange, all wave, over gravel road	Gier-Dunkle-type, aspirated radiometer with recording, multipoint potentiometer	27 June-14 July 1 Aug -15 Aug
	Station 3 **On Ice: 3 Miles Out on the Ice Cap, El 2460 ft**	
Air temperature at 4 ft	Hygrothermograph in standard weather shelter	7 July-16 July 23 July- 2 Aug 7 Aug -26 Aug
Air temperature at 4, 8, and 16 ft	Thermocouples in radiation shields with recording, multipoint potentiometers	29 July- 2 Aug 8 Aug -19 Aug
Wind speed at 4 and 8 ft	Anemometer, ML-80, with operations recorder	14 July-20 July 25 July- 2 Aug 9 Aug -20 Aug
Relative humidity at 4 ft	Hygrothermograph in standard weather shelter	7 July-12 July 8 Aug -19 Aug
Solar radiation, total incoming, all wave	Gier-Dunkle-type, aspirated radiometer with recording potentiometer	29 July- 2 Aug 8 Aug -19 Aug

at Station 1 on the ground. At Station 3, 3 miles out on the ice cap, there were only 30 days when the average daily temperature rose above 32 F, and the highest daily temperature recorded was 38 F. Thus, in 1956, Station 3 and the end of the Ramp Road were located quite close to the firn line, and the snow cover never completely melted during the thaw season.

The occurrence of high winds, blowing snow, and generally stormy weather was no more frequent in 1956 than may be considered normal. Six days of construction were lost during the season because of bad weather which occurred in four widely spaced intervals, as shown in Figure B2, Appendix B. Activities such as surveying had to be stopped on several occasions when blowing snow reduced visibility.

The amount of snow accumulation on the surface is more pertinent to construction planning than the amount of snowfall. Upon arrival of the field party at TUTO in 1956 (4 June) it was apparent that the snow accumulation from the winter and/or spring was greater than in previous years. Judging from snow depths on the open ramp, approximately 1 ft more of snow was present. On the ground, this larger amount of snow cover resulted in drifts 10 to 15 ft high around parked vehicles, equipment, and buildings. On the ice ramp, depths of snow ranged from 3 to 10 ft. Because of the late start of thawing temperatures and the relatively cool summer season, the snow cover was not substantially melted until the first week in July. During July and August snowfalls were frequent, and on several occasions accumulation was substantial. On one occasion, snow fell for 3 days (19-21 July), reaching a depth of 6 to 12 in. Therefore, work stoppages and delays in 1956 were caused more by snow cover than by any other single weather factor. Moreover, difficulties because of excessive snow cover were greater in 1956 than in either of the two previous years or the following year.

1957 weather

12. *Equipment.* The same three weather stations maintained in 1956 were reoccupied in 1957 by the U. S. Army Signal Corps Meteorological Detachment. Table IV lists the measurements made, equipment used, and period of record. Although equipment and personnel were adequate in number and efficiency, two major difficulties prevented the obtaining of complete data for the season. A delay in shipment of thermocouple wire and recording potentiometers prevented continuous determination of air and subsurface temperatures and the use of all solar radiation measuring devices prior to 6 July. The storm of 20 July put the instruments out of operation and forced personnel to vacate the stations. Therefore measurements were missed on several days.

Review of 1957 weather. A graphic summary of weather data for 1957 is given in Appendix B, Figures B3 and B4.

It is apparent from the air temperature records that 1957 was unusually warm. Not only was the daily average air temperature higher than in previous years, but thawing temperatures commenced earlier and continued later. The air thawing index* at Station 1 was 50% higher than the average air thawing index of the three previous years of record (Table V). The warm air temperatures were particularly noticeable at Station 3 where ordinarily thawing temperatures do not prevail long enough to melt the snow cover; in 1957 above-freezing temperatures were nearly continuous from early June to the middle of August. Results of such a warm season are obvious. Meltwater flow on the ramp and in runoff streams attained a magnitude beyond any anticipated. Ablation of the ice surface was unusually large. Thaw of the frozen ground was early and rapid, permitting borrow operations appreciably earlier than anticipated.

The year 1957 was also unique in that high winds occurred frequently. Moreover, the daily average wind speed for the season was higher than that of other years. On 20 July, the worst windstorm

* See Definitions.

Table IV. 1957 Meteorological Stations and Equipment

Measurement	Instruments	Period of Record
Station 1 — On Ground: 300 ft from Edge of the Ice Cap, El 1600 ft		
Standard hourly observations recorded on WB Form WBAN-10 included air temperature, barometric pressure, relative humidity, precipitation, dew point, visibility, cloud cover, and surface conditions	Hygrothermograph, maximum-minimum thermometers, and barograph, ML-3, in standard weather shelter Precipitation gage, ML-17 Precipitation gage, weighing type Psychrometer, ML-24	1 June-31 Aug
Air temperature at 7.5 and 50 cm, and at 1, 2, and 4 m	Thermocouples in radiation shields with multipoint, recording potentiometers	6 July-31 Aug
Wind speed and direction at 7.5 and 50 cm, and at 1, 2, and 4 m	Beckman-Whitley-type wind speed and direction set with operations-type recorder	28 May -31 Aug
Ground temperatures at surface, -2.5, -5.0, -7.5, -10, -20, and -25 cm	Thermocouples with multipoint, recording potentiometers	6 July-31 Aug
Sunshine duration	Marvin-type, black-bulb meter with operations recorder	1 June-31 Aug (Data missing for 31 days)
Solar radiation, all wave, total hemisphere	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	6 July-31 Aug
Solar radiation, all wave, net exchange	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	6 July-31 Aug
Solar radiation, short wave, incoming	Eppley-type pyrheliometer with multipoint, recording potentiometer	6 July-31 Aug
Solar radiation, short wave, outgoing	Eppley-type pyrheliometer with multipoint, recording potentiometer	6 July-31 Aug
Standard upper air observations (rawinsonde)	Recorder, radiosonde AN/TMQ5, rawin set AN/GMD-1A	26 June-31 Aug
Station 2 — On Ice: 1 Mile Out on the Ice Cap, El 1800 ft		
Standard hourly observations recorded on WB Form WBAN-10 included air temperature, barometric pressure, relative humidity, dew point, precipitation, visibility, cloud cover, and surface conditions	Hygrothermograph, maximum-minimum thermometers, and barograph, ML-3, in standard weather shelter Precipitation gage, ML-17 Precipitation gage, weighing type Psychrometer, ML-24	1 June-31 Aug
Air temperature at 7.5 and 50 cm, and at 1, 2, and 4 m	Thermocouples in radiation shields with multipoint, recording potentiometers	9 July-31 Aug
Wind speed and direction at 7.5 and 50 cm, and at 1, 2, and 4 m	Beckman-Whitley-type wind speed and direction set with operations-type recorder	28 May -31 Aug
Ice temperatures at surface, -2.5, -5.0, -7.5, -10, -20, and -25 cm	Thermocouples with multipoint, recording potentiometers	9 July-31 Aug
Solar radiation over snow or ice surface, all wave, total hemisphere	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	9 July-19 July 27 July-31 Aug
Solar radiation over snow or ice surface, all wave, net exchange	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	9 July-19 July 27 July-31 Aug
Solar radiation over gravel road surface, all wave, net exchange	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	16 July-19 July 27 July-31 Aug
Solar radiation over snow or ice surface, short wave, incoming	Eppley-type pyrheliometer with multipoint, recording potentiometer	9 July-19 July 27 July-31 Aug
Solar radiation over snow or ice surface, short wave, outgoing	Eppley-type pyrheliometer with multipoint, recording potentiometer	9 July-19 July 27 July-31 Aug
Station 3 — On Ice: 3 Miles Out on the Ice Cap, El 2460 ft		
Standard hourly observations recorded on WB Form WBAN-10 included air temperature, barometric pressure, relative humidity, dew point, precipitation, visibility, cloud cover, and surface conditions	Hygrothermograph, maximum-minimum thermometers, and barograph, ML-3, in standard weather shelter Precipitation gage, ML-17 Precipitation gage, weighing type Psychrometer, ML-24	1 June-31 Aug
Air temperature at 7.5 and 50 cm, and at 1, 2, and 4 m	Thermocouples in radiation shields with multipoint, recording potentiometers	11 July-31 Aug
Wind speed and direction at 7.5 and 50 cm, and at 1, 2, and 4 m	Beckman-Whitley-type wind speed and direction set with operations-type recorder	28 May -31 Aug
Ice temperatures at surface, -2.5, -5.0, -7.5, -10, -20, and -25 cm	Thermocouples with multipoint, recording potentiometers	11 July-31 Aug
Solar radiation over snow or ice surface, all wave, total hemisphere	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	11 July-20 July 27 July-31 Aug
Solar radiation over snow or ice surface, all wave, net exchange	Gier-Dunkle-type, aspirated radiometer with multipoint, recording potentiometer	11 July-20 July 27 July-31 Aug
Solar radiation over snow or ice surface, short wave, incoming	Eppley-type pyrheliometer with multipoint, recording potentiometer	11 July-20 July 27 July-31 Aug
Solar radiation over snow or ice surface, short wave, outgoing	Eppley-type pyrheliometer with multipoint, recording potentiometer	11 July-20 July 27 July-31 Aug

Table V. Comparison of Thaw Seasons, TUTO and Vicinity

Station	1954	1955	1956	1957	Avg
Thule Air Force Base, el 200 ft					
Start of thaw season	29 May	4 June	15 June	2 June	
End of thaw season	13 Sept	2 Sept	8 Sept	23 Sept	
Duration of thaw season, days	107	91	86	114	
Air thawing index, degree-days F	779	688	745	1217	857
Average air temperature for thaw season, °F	39.3	39.6	40.7	42.7	40.6
Camp TUTO					
Met. Sta 1, el 1600 ft					
Start of thaw season	22 June	7 June	15 June	8 June	
End of thaw season	28 Aug	17 Aug	19 Aug	28 Aug	
Duration of thaw season, days	68	72	66	82	
Air thawing index, degree-days F	508	397	380	606	473
Average air temperature for thaw season, °F	39.5	37.5	37.8	39.4	38.5
Met. Sta 2, el 1840 ft					
Start of thaw season	28 June	17 June	20 June	8 June	
End of thaw season	28 Aug	15 Aug	18 Aug	27 Aug	
Duration of thaw season, days	62	60	60	81	
Air thawing index, degree-days F	258	108	238	427	258
Average air temperature for thaw season, °F	36.2	33.8	36.0	37.3	35.8
Met. Sta 3, el 2460 ft					
Start of thaw season	NR	NR	(26 June) (28 July)	8 June	
End of thaw season	NR	NR	(10 July) (12 Aug)	19 Aug	
Duration of thaw season, days	NR	NR	30*	73	
Air thawing index, degree-days F	NR	NR	72*	294	NR
Average air temperature for thaw season, °F	NR	NR	34.4	36.0	NR
Hard Top (end of Ramp Road), el 2410 ft					
Start of thaw season	1 July	NR	NR	NR	
End of thaw season	25 Aug	NR	NR	NR	
Duration of thaw season, days	56	NR	NR	NR	
Air thawing index, degree-days F	119	NR	NR	NR	NR
Average air temperature for thaw season, °F	34.1	NR	NR	NR	NR

Note: NR = no record.

* The 1956 air thawing index at Station 3 includes the sum of degree-days of thaw for two periods of 15 days each. The algebraic total of degree-days of thaw for the entire summer was minus. The actual average air temperature from 26 June to 12 August was 30.5 F.

of the four seasons of record occurred; gusts greater than 90 mph were recorded. From 1 May to 31 August 1957, 21 working days were lost because of stormy weather. Fortunately, the longer thaw season provided sufficient additional time to make up that loss. High winds were responsible for more lost work time than any other single weather factor.

Snow cover at the start of the 1957 season was relatively light. The snow cover was almost completely melted on the first mile of the Ramp Road by 20 June, and from Mile 1 to Station 95+00 the snow was melted by 11 July. Beyond Station 95+00 snowstorms during the summer kept replacing the snow cover so that it varied between zero and 12 in. An unusual amount (more than 2.5 in.) of rain occurred, mostly in July, with as much as 0.5 in. in 1 day. Occasionally the precipitation was rain at Station 1 but snow at Station 3. However, snowfall, snow cover, and rain did not in themselves cause much work stoppage except when accompanied by high winds.

Analysis of TUTO weather

13. Although 4 years of weather recording are insufficient for determining average climate,

certain limits and characteristics are indicated. They are summarized herein to provide information for future planning for construction or investigational projects, and to define the conditions under which the construction and research activities of Project 1 were conducted. The effect of weather on the ground and ice surface and on working conditions is so great that even small variations in seasonal weather characteristics become highly significant.

The thaw season. The length and intensity of thaw in the summer season are important considerations in defining the work season for construction requiring such operations as excavating, borrowing materials, and erecting facilities on the ice surface. Table V lists the air temperature characteristics of the 1954, 1955, 1956, and 1957 thaw seasons. For comparison, the data for Thule AFB are listed with those of the three stations at TUTO. At Camp TUTO the length of the thaw season varied by as much as 22 days, and the date of its start and/or end by as much as 2 weeks. In planning a summer work season, a 72-day thaw season can be expected, beginning approximately 13 June and ending approximately 22 August. However, plans must be flexible enough to take advantage of an earlier start of thaw or a later end of thaw and, if necessary, to accomplish the work in a shorter season.

The amount of heat available for thawing in any one summer varies, primarily because of variation in the length of the season (see air thawing indexes in Table V). This variation in the heat supply results in a very large variation in the amount of snow and ice that is melted on the ramp and consequently in the quantity of meltwater runoff. The annual snow cover is melted rapidly or slowly, depending on the characteristics of the early part of the thaw season. Records are incomplete for Stations 2 and 3 on the ice cap, but it is apparent in Table V that the pattern of variation in length of thaw season at Camp TUTO is followed throughout. However, as the elevation at which no thaw occurs is approached (Station 3), the variation in length of thaw season has a more drastic effect on the surface. A short, cool season can result in little or no melt of the snow cover, whereas a long, warm season can melt not only the winter snow cover but also a substantial thickness of ice.

Figure 5 shows the variation of air thawing index with elevation for the years 1956 and 1957. In both years (see also report of 1955 investigations[6]) the rate of decrease of the air thawing index per unit increase in elevation is much greater as the edge of the ice cap is crossed and ascended than is the rate over the land area or on the ice cap beyond the first 2 miles of ramp (el 2200). The immediate effect of crossing from the ground to the ice cap is a drop in air temperature, a decrease in the length of the thaw season, and a decrease in the air thawing index that is not commensurate with the increase in elevation.

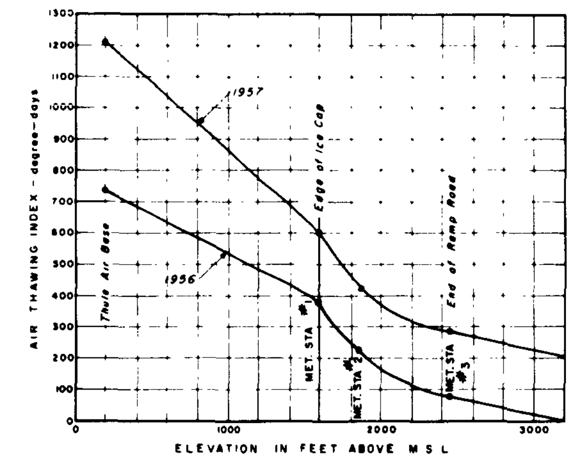


Figure 5. Air thawing index versus elevation.

It is important to note that where the ice margin has a comparatively gentle slope, as at TUTO (3 to 7%), the elevation where no melt or an insignificant amount of melt will occur varies considerably from year to year.

Workdays lost due to inclement weather. The number of workdays which may be lost because of weather is dependent upon the nature of the work. Road construction work can usually continue unless very high wind, extreme cold, excessive snowfall, or a combination of these conditions occurs and personnel cannot effectively remain in the open (unsheltered).

In 1954, 1955, and 1956, 6 days per season were lost by the construction crews. During 1957,

an abnormal season weatherwise, 10 days were lost. Thus, it may be assumed that from 6 to 10 days of construction work will be lost in an average summer season.

More precise work, such as surveying, is hindered to a much greater extent than construction activities. Poor visibility because of fog or blowing snow is the usual cause of delay in survey work. The number of days lost for this category of work is usually at least twice that for construction work, or from 12 to 20 days per season.

Very specialized activities, such as photography, may be hampered more than 20 days per season by adverse weather conditions.

Snow conditions. At TUTO the difficulty of measuring snowfall is even greater than usual in the Arctic because high winds and blowing snow nearly always accompany a snowfall. Moreover, records of previous winters are not available. Therefore, the average annual snowfall pattern cannot be described.

Again because of high winds, snow cover on the ground is extremely variable, ranging from zero on the tops of ridges and hills to 10 or 15 ft in the lee of hills, in gullies or valleys, or against an obstruction such as a building or a parked vehicle.

On the relatively smooth surface of the ramp, the snow cover is more consistent, returning annually in approximately the same pattern. Figure 6 shows the average snow depth on the ramp at the start and end of the thaw season. Note that the snow depth is greatest on the first 1/2 mile of

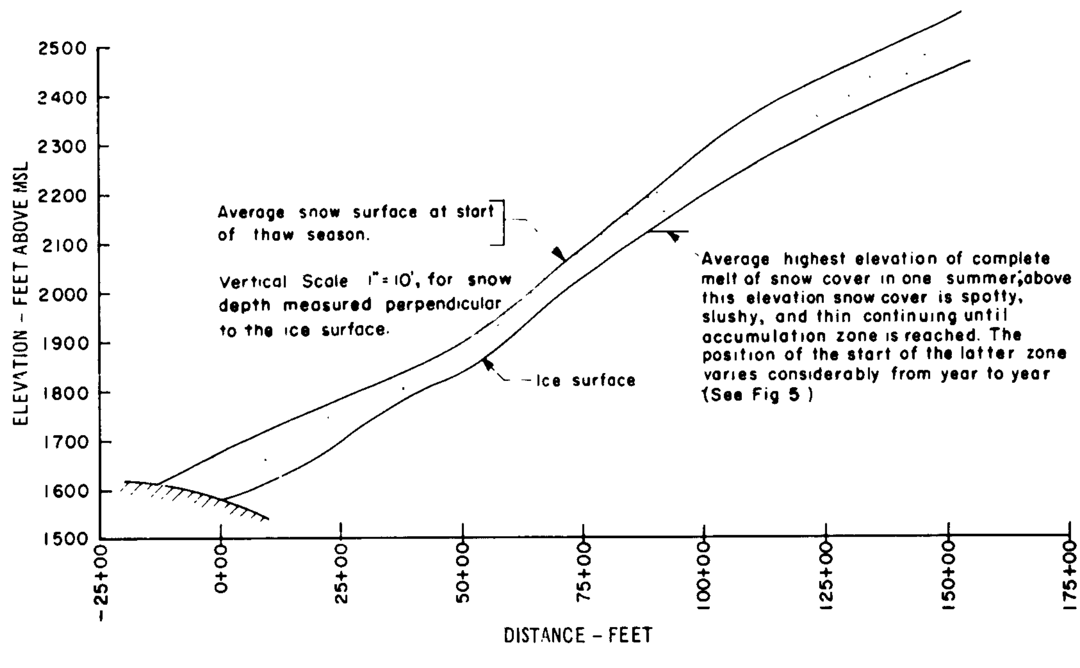


Figure 6. Average snow cover at start of thaw season, TUTO Ramp.

the ramp. In the last week of June or the first week of July the snow cover becomes isothermal at +32 F and very wet, and at times the snow in lower places may become saturated, in which condition even light-ground-pressure vehicles cannot be supported. Ice is exposed first where the thinnest snow cover exists at approximately Station 30+00, then at the first 1/2 mile. Thereafter, the extent of the bare ice zone increases all summer, usually reaching as far as about Station 90+00. Beyond this station there is usually some snow cover, although it may be thin and slushy, until the

accumulation zone is reached. The start of the accumulation zone varies from season to season, and may be from 1 to 5 miles beyond the start of the slush zone. In 1957 the pattern was somewhat different; that is, the greater depth of snow in the first 1/2 mile of the road was not so pronounced. Possibly the high, perched Transverse Road and Ramp Road affected the surface wind pattern.

Summary

14. The Meteorological Branch, U. S. Army Signal Corps, set up and operated three weather stations (one on land and two on ice) in the TUTO area during the thaw seasons of 1956 and 1957. Their program of investigation included micrometeorological-type measurements as well as standard weather observations. Data for 1956 were incomplete; data for 1957 were nearly complete.

The 1956 thaw season was cool and short, and was characterized by a deep snow cover and large drifts in the early part of the season.

The 1957 thaw season was long and warm with an air thawing index 50% greater than that for any of the previous 3 years. The season was also unusually windy. The winds of one storm were in excess of 90 mph, and wind speed for the entire season averaged about 5 mph above that of previous seasons.

From 1954 to 1957, inclusive, the average length of the thaw season at Camp TUTO was 72 days, commencing 13 June and ending 22 August. It varied as much as 2 weeks in the starting or ending date and in length. The average temperature for the thaw season was 38.5 F.

The air thawing index decreased very rapidly with rise in elevation along the first 2 miles of ice ramp.

From 6 to 10 days work on road construction was lost in one thaw season in the TUTO area due to inclement weather, and for as many as 20 days in one thaw season weather was unsuitable for surveying or similar activities.

At the end of the snowfall season, snow cover on the land areas near TUTO varied from zero on the ridges and hills to 10 ft or more in the lee of hills, in gullies, and in valleys. On the ice ramp, the snow cover varied from 3 to 4 ft on the first mile, 1-1/2 to 2-1/2 ft on the next 1/2 mile, and from 3 to 4 ft thereafter.

IV. PHYSIOGRAPHY AND SOILS OF THE TUTO AREA

15. A study was made of the soil properties and physiography of an area encompassing 10 to 15 square miles in the immediate vicinity of Camp TUTO. Primarily the study was made to obtain a knowledge of the soils available for use as borrow materials and to obtain data necessary for the design of roads, building foundations, and other facilities. In addition, detailed measurements were made of surface soil properties to complete the information that, together with meteorological data, was required for making computations to predict rate and depth of thaw.

As can be seen in Figure 1, Camp TUTO is located near the edge of the ice cap, 20 miles inland from Baffin Bay. It is situated on a large moraine[14] at an elevation averaging 1550 ft above mean sea level. The surface is essentially a rolling or gently undulating boulder plain characterized by "patterned ground." The patterns range in diameter from 5 to 15 ft, usually with slightly raised centers, surrounded by trenchlike depressions filled with cobbles and boulders (Fig. 7). The patterns are irregular in shape, and rings, polygons, and stripes may be discerned.

Figure 7. Typical ground surface in TUTO area.
Note patterned ground (17 Aug 1955).

Some variation in surface soil types is apparent. Several small areas were found where the surface soils were predominantly sand or silty sand with relatively few boulders. In these places the patterns are less well defined.

There are no bedrock outcrops in the immediate TUTO area, and the depth of overburden has never been determined. It is reported[8] that Camp TUTO is underlain by sedimentary rock. To the south there is a metamorphic rock complex separated from the sedimentary beds by a fault. Boulders of sedimentary, metamorphic, and igneous rocks are present on the surface around Camp TUTO, with the igneous rocks occurring infrequently. The igneous rocks are mainly gabbro and are similar to gabbro dikes present in the Thule area. Around TUTO, metamorphic boulders predominate, including granitic gneisses and hornblende, chlorite, and garnetiferous schists.

Drainage in the area is largely concerned with dispersion of the meltwater from the ice cap. At the base of the moraine formation bordering the edge of the ice cap is the large lake called Lake TUTO. The lake is fed by melting snow and ice from the ice cap, and consequently the water level rises and falls in proportion to the degree of melting under way at any particular time. As shown in Figure 1, a stream running west along the north edge of the camp drains the lake. Another stream commencing on the south side of the Ramp Road runs along the edge of the ice cap and out through a small east-west valley south of Camp TUTO. Both streams merge and form the South Branch of the Sioraq River. For a period of 2 or 3 weeks in the spring, melting of snowbanks and frozen ground causes surface ponding in localized areas.

Active zone

16. The depth of thaw of the undisturbed ground in the TUTO area varies from about 32 to 44 in., depending upon the soil characteristics and the intensity of the summer thaw season. A depth of 39 in. predominates over most of the area in a normal or average season.

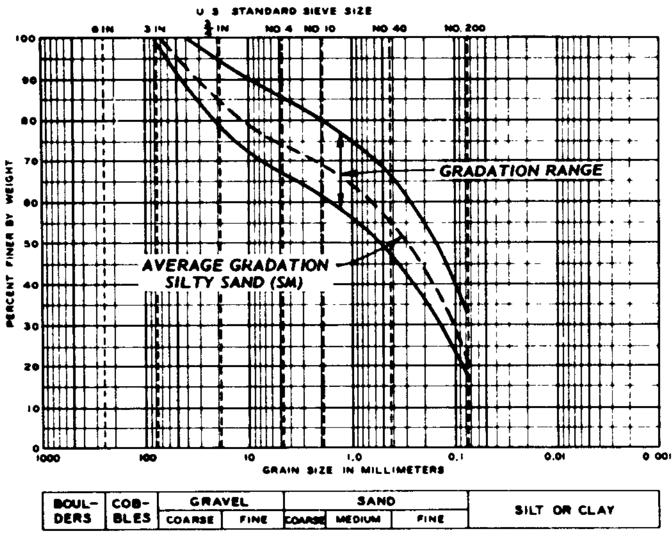
Typical soil characteristics. About 80% of the surface of the area investigated is characterized by the patterned ground formation, with large boulders and cobbles at the periphery of the patterns. Figures 8, 9, and 10 show typical areas. During the thaw season, test pits were dug at several locations (see Fig. 2), and the depth of thaw was measured once a week. At the same time, the water content of each 6-in. layer to top of frozen ground was measured. Once during the season the density and gradation of each 6-in. layer was determined. This investigation program was continued from 1955 through 1957. Figures 8 and 9 give the average of all density and water contents measured for each 6-in. layer of thawed soil during the 3 years of observations together with the average and range of gradation of soils in the active zone. Figure 10 gives the same data except for random depths and for 1957 only. The test pits were dug in the center of the pattern formation, and therefore test results do not include the boulders and cobbles at the edge of the patterns. It will be noted that nearly identical soil (silty sand with varying amounts of gravel) exists at all locations tested, that the dry density averages about 120 lb per cu ft in all layers and at all locations, but that the water content varies between 7 and 14%. In effect, therefore, the only significant difference in soil properties is in the water content, which varies from place to place and from time to time during the thaw season. In general, a high water content resulting from melting snow or from the rise of a meltwater stream or the lake does not persist for more than a few days, as the water tends to drain from the soil into the boulder-filled, trenchlike depressions at the edge of the pattern formations. A high water content usually exists in the 6-in. layer above the frost table; this accounts, in part, for the increase in water content with depth for each test pit, as shown in Figures 8, 9, and 10.

Fine-grained surface soil. Not typical of the TUTO area, but illustrating the variety of soils possible in the terrain, is the area represented by the data for test pit 4 given in Figure 11. As discovered by the deep core-drilling operations, this area contains a lacustrine deposit. However, in the active zone, which at this location is 40 to 44 in. deep, the freeze-thaw action has apparently destroyed the varves. No definite pattern formation is apparent on the surface. The soil has been classified as a clayey sand, but the percentage of clay and silt varies considerably with depth. Generally the top 18 in. is coarse (predominantly sand) and the next 18 in. predominantly clay or silt. The density averages 123 lb per cu ft, and the water content ranges from 8.2% at the top to 11.8% at the bottom. The water content does not vary appreciably during the thaw season.

Other types of surface soils. In some small areas, the surface is predominantly sand or cobbles and boulders. In these areas some type of specialized sorting has taken place. Where cobbles and boulders occur in quantity, the area has obviously been washed by flowing water as shown by the fact that such areas are found on the lee side of fairly steep slopes or in old streambeds where snow fields remain until late in the thaw season. Sandy surfaces occur in high, flat areas where drainage is good but where there is no flowing water. These areas are usually small and contain no large boulders or well-defined patterns. The sandy and bouldery areas were used for borrow materials. Their soil properties will be discussed subsequently in more detail.

Permafrost

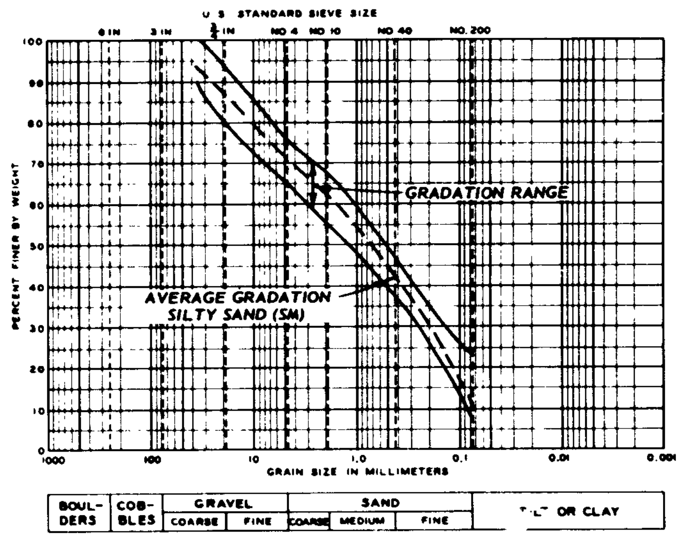
17. The entire TUTO area is underlain by permafrost beginning from 3 to 4 ft beneath the surface and extending to an unknown depth. Exploration of the permafrost has been primarily by core drilling, although in 1954 a few test pits were excavated to depths of 5 ft.[5] A very successful program of core drilling was conducted in 1956. Four holes, designated D3, D4, D5, and D6, were drilled to depths of from 40 to 60 ft. Frozen cores were extracted with nearly 100% recovery from 10 ft below the surface to bottom of hole. In 1957, holes D7, D8, and D9 were drilled to depths of 20 ft to investigate the properties of the top 10 ft of permafrost. Density tests were run on the frozen cores as they came from the core barrel by weighing suitable-size chunks in cold diesel oil (the specific gravity of the diesel oil was determined with a hydrometer). The samples were then placed in airtight cans and transmitted to a field laboratory for moisture content and gradation tests. When necessary for classification, tests for Atterberg limits were conducted.

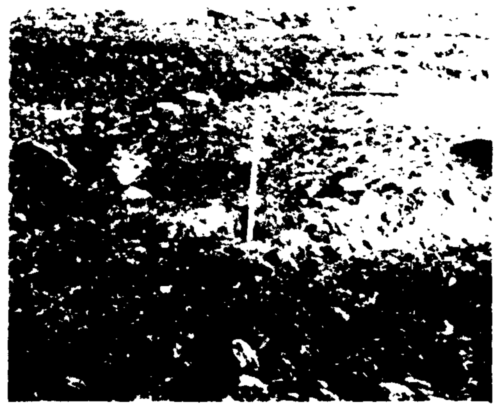


DEPTH IN.	DRY DENS. pcf	MOIST. CONT. %
0–6	120	10.3
6–12	122	11.7
12–18	123	12.7
18–24	123	12.4
24–30	121	11.5
30–36	—	13.9
AVERAGE MAXIMUM DEPTH OF THAW = 37"		

NOTE: GRADATIONS, DENSITIES, AND MOISTURE CONTENTS ARE THE AVERAGE OF TESTS CONDUCTED IN 1955, 1956, AND 1957.

Figure 8. Typical section of surface soil, test pit 6.

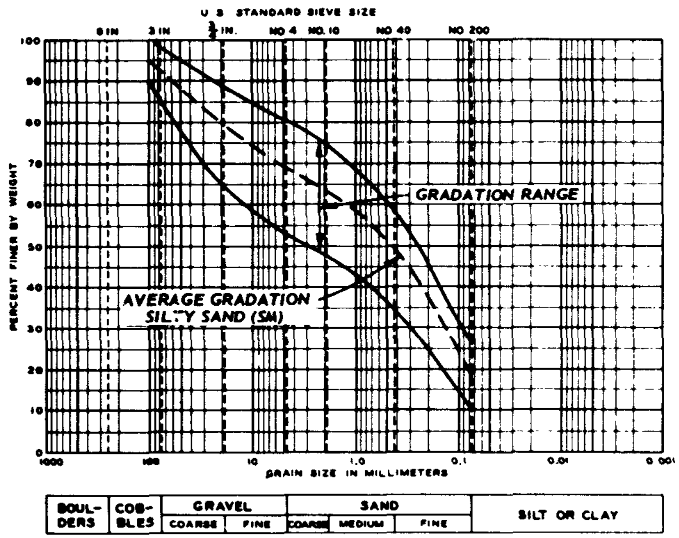


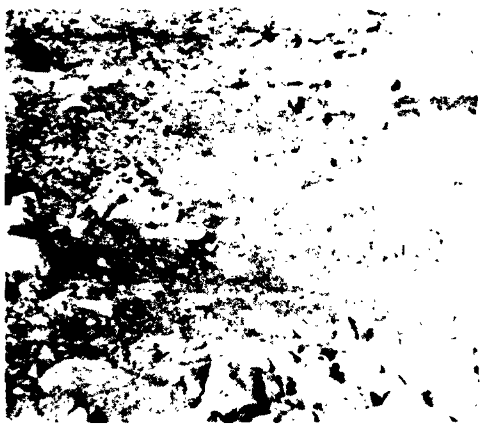


DEPTH IN.	DRY DENS. pcf	MOIST. CONT. %
0–5	116	13.9
5–10	122	11.5
10–14	126	9.4
14–18	131	9.1
24–29	133	9.0
29–34	131	9.3
34–37	142	12.1
37–41	132	10.8
AVERAGE MAXIMUM DEPTH OF THAW = 42"		

NOTE: GRADATIONS, DENSITIES, AND MOISTURE CONTENTS ARE THE AVERAGE OF TESTS CONDUCTED IN 1957.

Figure 9. Typical section of surface soil, test pit 7.

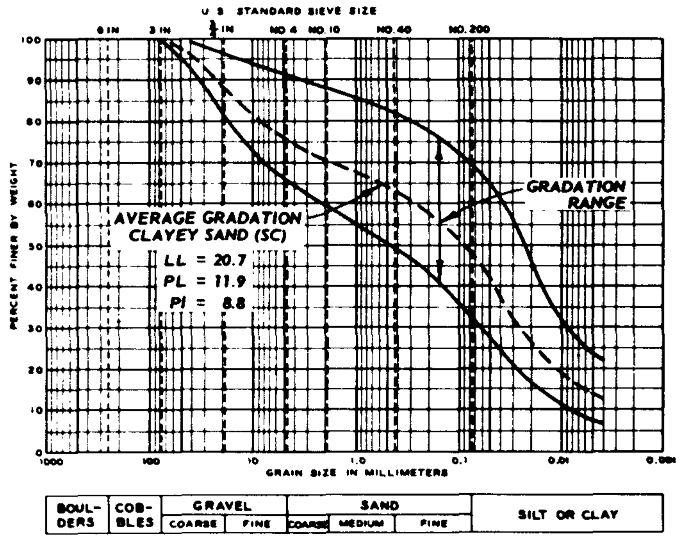




DEPTH IN.	DRY DENS. pcf	MOIST. CONT. %
0–6	118	7.4
6–12	119	8.4
12–18	122	9.1
18–24	125	10.8
24–30	120	10.5
30–36	—	13.4
AVERAGE MAXIMUM DEPTH OF THAW = 39"		

NOTE: GRADATIONS, DENSITIES, AND MOISTURE CONTENTS ARE THE AVERAGE OF TESTS CONDUCTED IN 1955, 1956, AND 1957.

Figure 10. Typical section of surface soil, test pit 8.



DEPTH IN.	DRY DENS. pcf	MOIST. CONT. %
0–6	124	8.2
6–12	122	9.0
12–18	123	11.0
18–24	120	11.8
24–30	124	11.1
30–36	124	11.2
36–42	—	8.9
AVERAGE MAXIMUM DEPTH OF THAW = 42"		

NOTE: GRADATIONS, DENSITIES, AND MOISTURE CONTENTS ARE THE AVERAGE OF TESTS CONDUCTED IN 1955, 1956, AND 1957.

Figure 11. Section of small area of clayey sand, test pit 4.

Drilling procedure. Methods of core drilling in frozen, coarse-grained soil had not been developed to the extent that success was at all certain. Thus the core-drilling operations were experimental in themselves, and were performed to aid in the development of suitable methods.

Standard equipment, more or less readily available, was used almost exclusively (Fig. 12). The drill rig had a 27-ft mast, hydraulic feed with a 30-in. stroke, and a pump of 70-gpm capacity. A portable, sheet-metal slush pit of 150-gal capacity was provided. Drill rods were size NX. Standard double-tube, swivel-head, 4- by 5-1/2-in. core barrels were used with both split-ring and basket-type core lifters. Both 5- and 10-ft nominal lengths were used. Special bottom-discharge diamond bits were furnished; the diamonds were impregnated in the matrix, in addition to surface-set diamonds.

Figure 12. Drill rig setup at hole D3. The base point "NN" was installed in this hole (14 June 1956).

The drilling fluid consisted of water and 2 to 3% by weight of aquagel or zeogel. The mixture was cooled by the addition of snow and common salt whenever the temperature of the return fluid rose above 31 F. The concentration of salt varied between 2 and 4%. The rate of fluid circulation varied between 10 and 30 gpm. The rotation of the bit varied between 90 and 200 rpm, and the oil pressure in the hydraulic feed system varied between 100 and 175 psi. These pressures correspond to bit pressures of 1300 to 3000 lb.

In 1956, a total of 213 ft of frozen soil was drilled, with core drilling through 191 ft. Full recovery was obtained in all holes below a depth of 10 to 11 ft. The primary cause of the failure to obtain full core recovery in the upper strata was the higher temperature range and the correspondingly lower strengths of the frozen soil. Further investigations are needed to develop methods of handling this situation. One method would be to accomplish the drilling during the colder months when both air and soil temperatures are well below freezing.

Complete details and discussion of the core-drilling procedures have been published by WES (reference 7).

Typical permafrost soil properties. Figure 13 shows graphic logs of holes D3, D4, D5, D7, D8, and D9. Holes D8 and D5 are shown together as if they were one hole, because although D5 was drilled in 1956 and D8 in 1957, the holes were located within 20 ft of each other (Fig. 2). Holes D3 and D9 are labeled separately but shown in conjunction with each other. These two holes are located 1545 ft apart, but they are at approximately the same elevation, on the same ridge, and in the same type of soil. The log of D6 was not included with the group because the varved silt and sand found at this location were certainly not typical of the area; the graphic log of this hole is shown in Figure 14. The soil beneath the ice of the ramp was investigated in drill hole D11A and is shown in Figure 14. Each core was photographed after its removal from the core barrel; some of these photographs have been combined to form pictorial logs of D5, D6, D8, and D11A, and are included in Appendix B, Figures B5, B6, B7, and B8.

Generally, the top 7 ft of permafrost (Fig. 13), from a depth of 3 to 10 ft, tends to be coarse-grained soils, consisting predominantly of sand or gravel with varying amounts of silt and occasionally a thin layer of silt (ML) or ice. The ice content is very high; the measured moisture content ranged from 10 to 100%. The ice is in the form of lenses up to more than 2 in. thick. The greatest amount of ice occurs at or just below the thaw line, gradually decreasing to the 10-ft depth. The drill holes shown in Figure 13 are all located in places where the boulder-polygon type of patterned ground is very pronounced. It is to be expected that large ice concentrations will be found at the thaw line since free water accumulates on the impervious permafrost and refreezes during the winter.

Figure 13 shows that below a depth of 10 ft the permafrost is a bouldery till (GP or GM, or combination of both). Occasional layers of fine soils (SP or SM) occur with thicknesses of from 6 in. to 2 ft; hole D3 shows a layer of silty sand (SM) 7 ft thick commencing at 20 ft. Boulders are mainly crystalline rock, up to 18 in. in diameter, occurring at random but tending to be larger and more frequent below a 35-ft depth. (More and larger boulders are found in the active zone and on the surface.) Ice usually coats the surface of soil grains, cobbles, or boulders, but occasionally a sizable lens or chunk of ice will be present just above a large boulder. In the coarse soils, 100% saturation is common. Dry densities range between 128 and 145 lb per cu ft, averaging 134 lb per cu ft. Moisture contents range from 3 to 13%, averaging 9%. The sand (SP and SM) layers contain more segregated ice, and consequently moisture content is frequently high and dry density low.

Figure 14 shows the log of the last 49 ft of drill hole D11A which is located 1800 ft from the edge of ice on the ice ramp. Before the underlying soil was encountered, 190 ft of ice was drilled. The log of D11A shows a finer soil than that in D5. It is classified as SM with an occasional layer of GP or GP-GM. The incidence of boulder occurrence increased with depth. All samples tested were 100% saturated, and there was almost no segregated ice. A pictorial log of hole D11A is shown in Figure B8, Appendix B. Note the occurrence of traces of vegetation 1.7 ft below the soil surface.

Lacustrine deposit. The log of drill hole D6 (Fig. 14) shows what is probably an unusual soil formation for the area, a lacustrine deposit 29 ft deep. The pictorial log in Figure B6, Appendix B, shows the varves quite clearly. Nothing in the present configuration of the terrain would suggest the presence of this deposit unless it be Lake TUTO, ostensibly a shallow meltwater pool but actually well over 150 ft deep. The deposit is primarily alternate varves of silt and sand with lenses of almost clear ice, but clay occurs in thin layers. These layers were usually too thin to sample, but tests for Atterberg limits at two places revealed plastic characteristics. A layer at 23.6 ft was found to have a plasticity index (PI) of 8.9, and a sample obtained by selecting the most plastic-appearing material in the 25- to 34-ft layer had a PI of 21.8. Several other tests of samples at various levels showed the soil to be nonplastic. Densities and moisture contents were determined in the manner described for the other holes. Since it was impractical to test each layer or varve, the results obtained from tests of sizable chunk samples reflect only the combined characteristics of the several types of soil and the ice. The soil was determined to be a sandy silt (ML). Density averaged 53 lb per cu ft in the first 5 ft and about 95 lb per cu ft down to the bottom of varved material. Moisture content

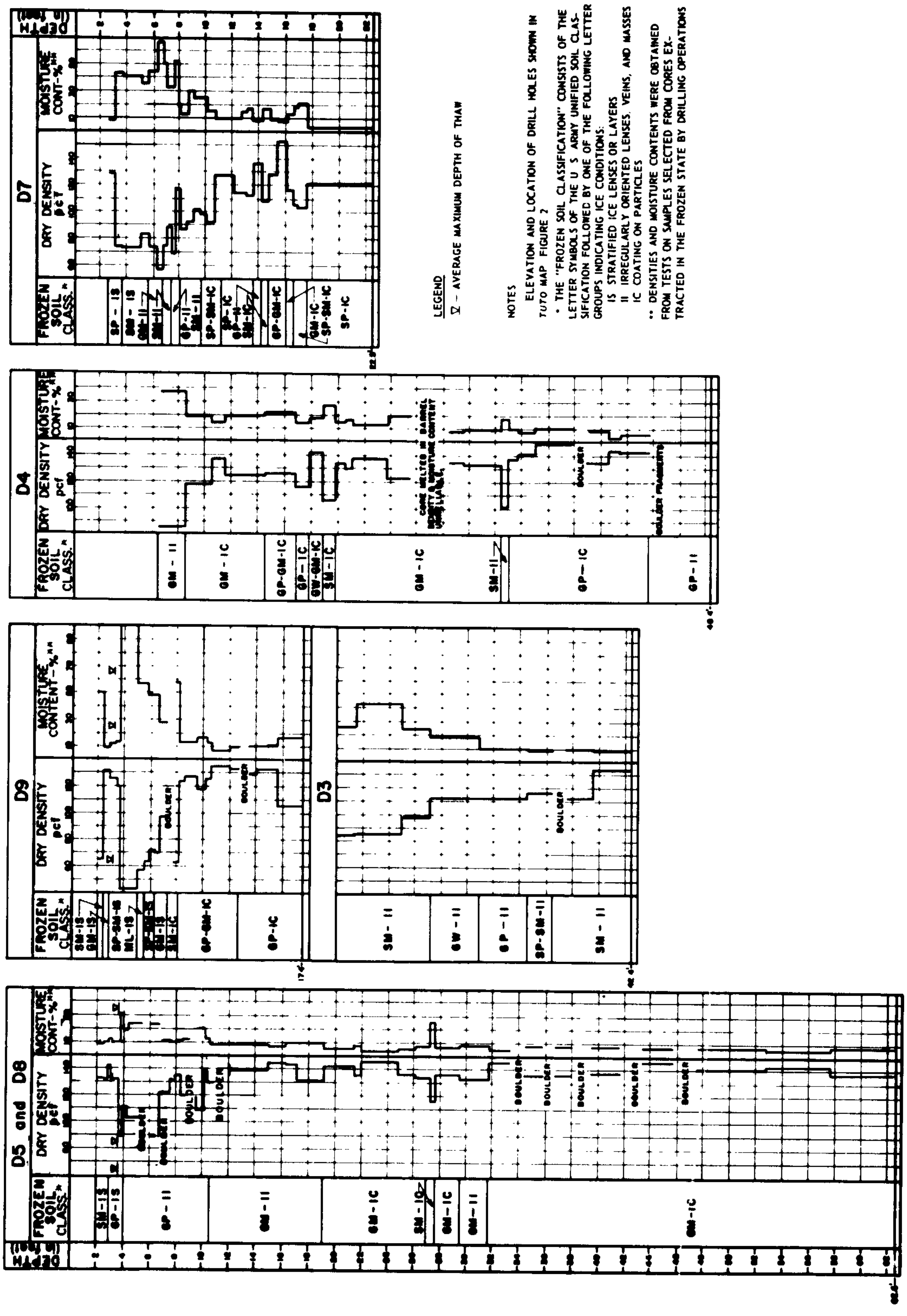
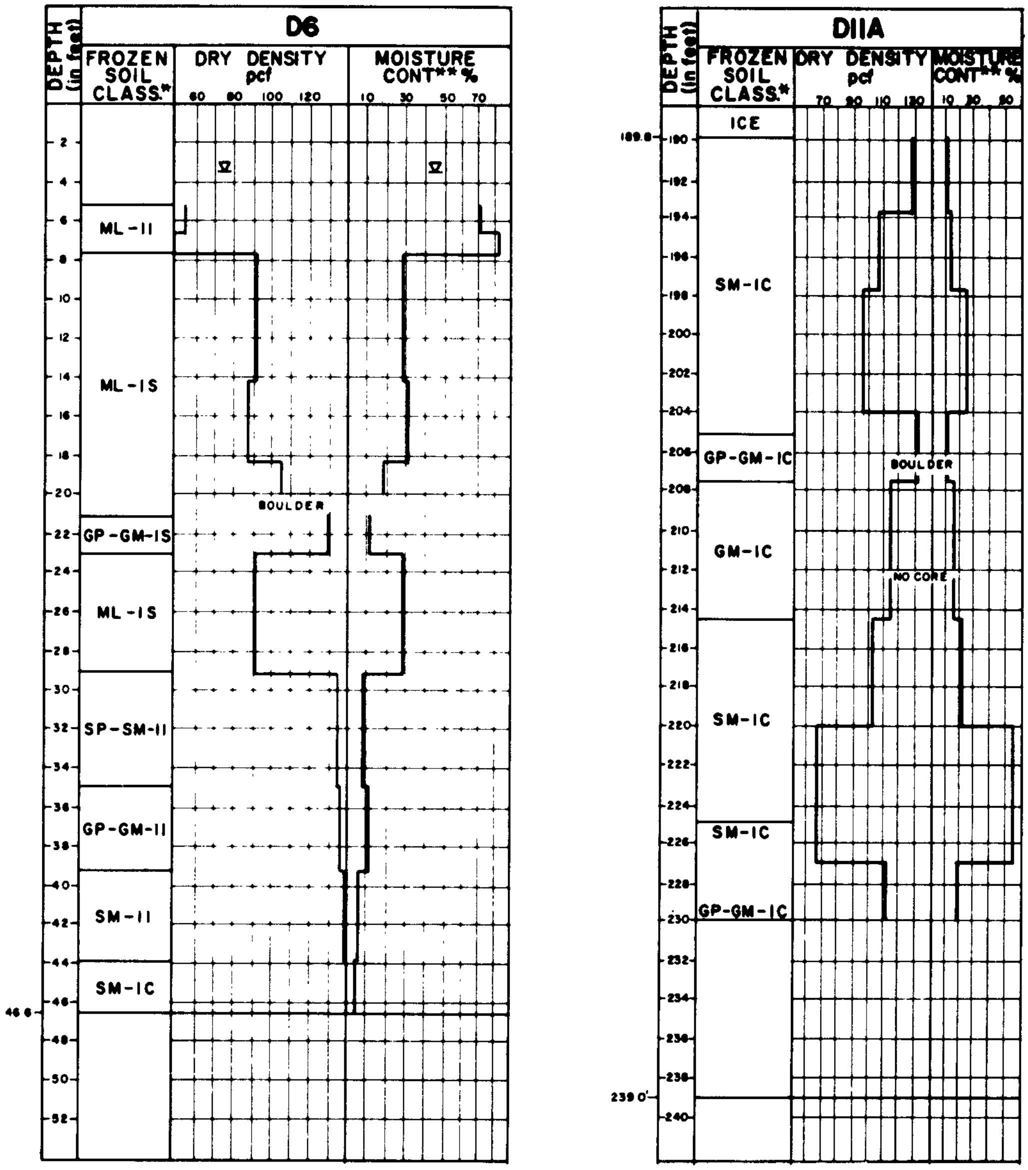


Figure 13. Logs of drill holes D3, D4, D5, D7, D8, and D9, TUTO area.



LEGEND

∇ - AVERAGE MAXIMUM DEPTH OF THAW

NOTES:

ELEVATION AND LOCATION OF DRILL HOLES SHOWN IN *TUTO* MAP, FIGURE 2.

* THE "FROZEN SOIL CLASSIFICATION" CONSISTS OF THE LETTER SYMBOLS OF THE U. S. ARMY UNIFIED SOIL CLASSIFICATION FOLLOWED BY ONE OF THE FOLLOWING LETTER GROUPS INDICATING ICE CONDITIONS:

IS STRATIFIED ICE LENSES OR LAYERS
II IRREGULARLY ORIENTED LENSES, VEINS, AND MASSES
IC COATING ON PARTICLES

** DENSITIES AND MOISTURE CONTENTS WERE OBTAINED FROM TESTS ON SAMPLES SELECTED FROM CORES EXTRACTED IN THE FROZEN STATE BY DRILLING OPERATIONS.

Figure 14. Logs of drill holes D6 and D11A, TUTO area.

averaged 77% in the top 5 ft and 26% thereafter. An exception was a layer of gravel at the 22-ft depth which had a dry density of 128.9 lb per cu ft and a moisture content of 10.6%. In the samples the varves were clearly visible, and the silt, sand, and ice layers could be identified by color and texture.

Commencing at 30 ft, the soil was similar to that in the other drill holes; i.e. a glacial till with boulders, densities from 134 to 140 lb per cu ft, and moisture contents from 4.6 to 10.1%.

Subsurface temperature

18. Strings of thermocouples for the measurement of temperatures to depths of 40 and 30 ft were installed in holes D6 and D5, respectively (Figs. 15 and 16). The range of temperatures

Figure 15. Thermocouple installation at hole D6, near test pit 4. Note absence of pronounced frost patterns in this area (4 July 1956).

Figure 16. Thermocouple installation at hole D5, near test pit 8. Note pronounced patterns (12 Aug 1958).

measured at various depths in D6 and D5 for the 1957 thaw season are shown in Figures 17 and 18, respectively. Difficulties in installation at D5 delayed the start of regular readings; therefore the record is not as complete as that for D6.

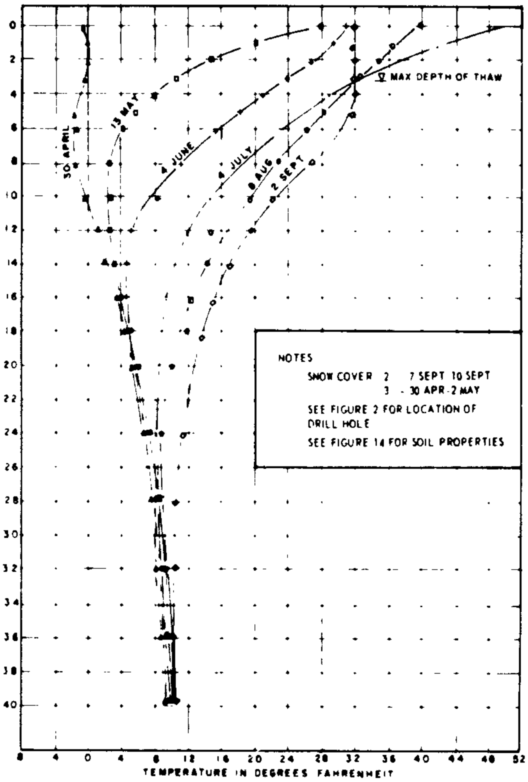


Figure 17. Typical subsurface temperatures in hole D6 for 1957 thaw season.

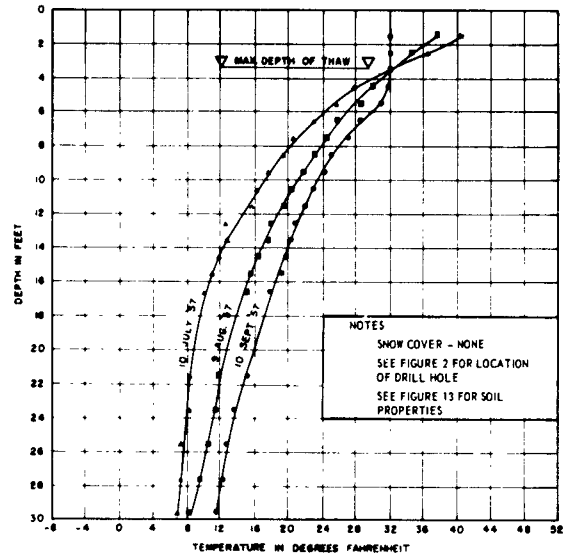


Figure 18. Typical subsurface temperatures in hole D5 for 1957 thaw season.

At the 40-ft depth the temperature variation is the least, and the prevailing average temperature is +10 F, varying a little less than ±2 F during the season. The variation may be partly due to the fact that the readings were accurate only to ±1/2 F. It was assumed that this temperature was approximately equal to the mean annual surface temperature.

The relatively low mean annual temperature distinguishes the permafrost of the Thule-TUTO area from that found in many other arctic areas where the temperature is much higher, even approaching 32 F. In general, the lower temperature means a greater frozen soil strength, other properties being equal. Calculations of rate and depth of thaw for various thawing indices must take into account the importance of the "sensible" heat factor, i.e. the heat required to raise the frozen soil to thaw temperature. This is in contrast to areas where the permafrost is relatively warm and the latent heat factor is dominant.

Borrow materials

19. Borrow materials for road construction on the ice should be (a) highly permeable for stability under wet conditions due to melting snow and ice, and (b) heavy, for stability under flowing meltwater. As such material would probably have a very rough surface when compacted into a road fill, a surfacing material is required which should be nonfrost-susceptible, free of boulders, and of such gradation that normal compaction procedures will produce a surface with adequate bearing capacity and durability for the heavy traffic to which it will be subjected. Other borrow requirements can be met without special selection.

Between the ice cap and the shoreline, borrow materials composed of a mixture of sand and gravel with varying concentrations of cobbles and boulders are available. Areas may be selected which contain very coarse materials suitable for road fills and similar construction on the ground and especially desirable for use on the ice. In addition, sufficient rock (boulders and cobbles) is available for limited crushing and screening operations. The shallow depth of thaw in the TUTO area is a deterrent to borrow operations. An economically feasible method of borrowing from the permafrost soils has not yet been developed, and all borrow has been from the active zone. The material is pushed into stockpiles by bulldozers, then loaded on dump trucks with a power shovel (Fig. 19). This type of operation permits satisfactory progress with a minimum of equipment.

Figure 19. Power shovel loading dump trucks with stockpiled material in Borrow Area D (5 July 1957).

Coarse, highly permeable soils. The gravel road fills on ice, and at other places where large quantities of flowing water occur, must be constructed of highly permeable, bouldery material. Such fill material was found in so-called "boulder" areas, usually on the lee side of hill slopes or in old streambeds where meltwater flow has washed the surface, removing the fines and leaving almost clean boulders and cobbles. These areas are usually about 2 ft deep, underlain by a layer of fine soil containing fairly high percentages of silt. Figure 20 shows a typical borrow area for this type of

Figure 20. Borrow area for coarse (cobbles and boulders) borrow (16 July 1955).

material. Figure 21 shows typical gradations of materials from several borrow pits used in 1955, 1956, and 1957. It will be noted that more than 50% by weight of this material is cobble and boulder size and that more than 90% is larger than 3/4 in. During the 3 years, 51,600 cu yd of this material was used in constructing roads on the ice surface. The locations of the three principal borrow pits (designated E, F, and L) from which the material was obtained are shown in Figure 2. Borrow pit L, the last pit used, is approximately 2 miles from the edge of the Ramp Road. All of the pits used to date are nearly depleted, and new pits will have to be located if any great quantity of coarse fill is required in future construction.

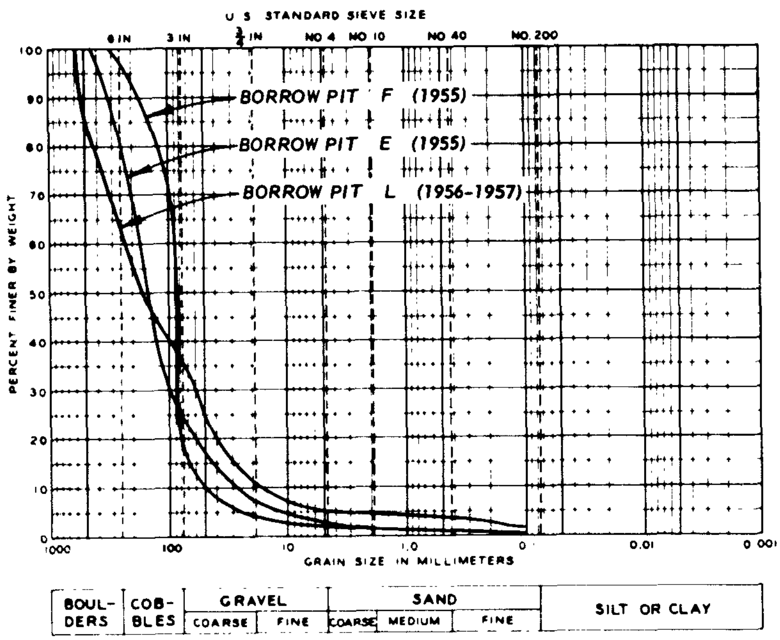


Figure 21. Typical gradations of coarse borrow soils.

Fine soils. It was necessary to surface the fills constructed of coarse soils to provide a smooth surface for vehicular traffic and to allow for grading and shaping operations. For this purpose, borrow areas were sought where the surface soil was relatively free of boulders and cobbles and contained a minimum of silt. Although soil with an ideal gradation was not found, an adequate type was found, as shown by the gradation curves in Figure 22. Note that borrow pit K, used in 1956-1957, yielded fairly satisfactory sand, but that pits D and H, used in 1955, contained a rather high percentage of silt. About 8500 cu yd of this soil was used to surface the roads on the ramp. A small amount is still available in borrow pit K, but a new location will have to be found if extensive new road construction is contemplated.

Random, mixed-type soils. As previously mentioned, there is an abundance of soil available in the active zone near Camp TUTO, which has been sorted into patterned ground formations. This soil can be bulldozed into stockpiles, mixing the boulders and cobbles at the periphery of the patterns with the silty sand of the center portion. The result is a bouldery till containing about 4% silt and 35% cobbles and boulders larger than 3 in. (Fig. 23). Where free-draining soil is needed, or one without large cobbles or boulders, this mixed type is unsuitable. However, its compaction characteristics are fairly good, and it was used for road fills and for building pads on the ground and dikes and berms on the ice. Approximately 13,850 cu yd of this material was used to construct berms and dikes on the ice.

Crushed rock. In the TUTO area, rock available for crushing is limited to the boulders and

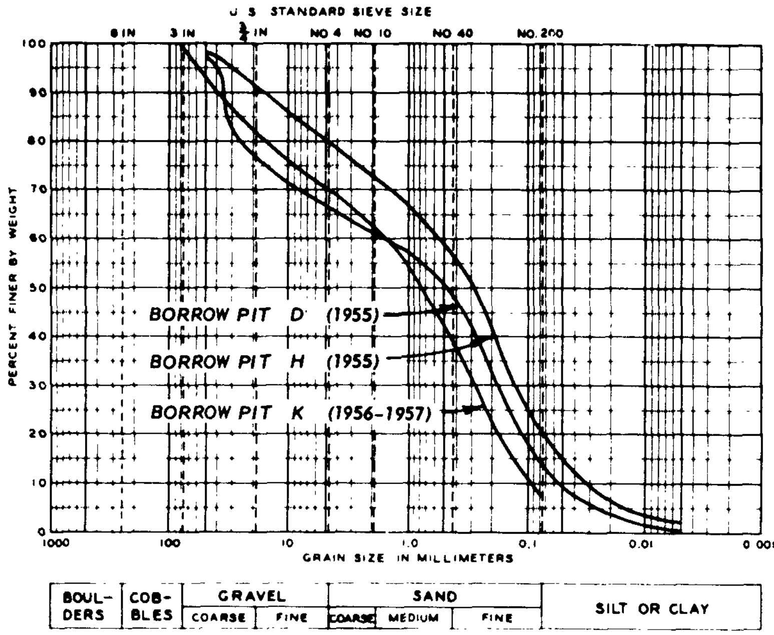


Figure 22. Typical gradations of fine borrow soils.

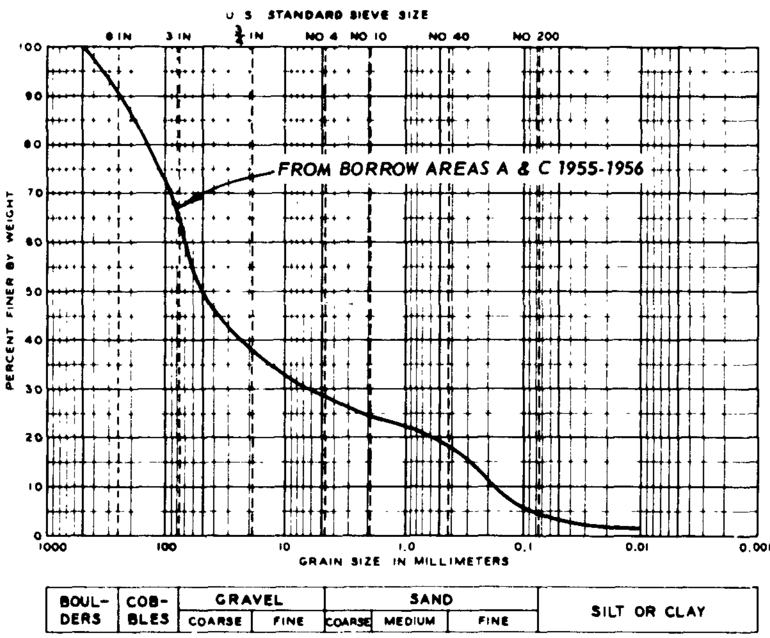


Figure 23. Typical gradation of random, mixed borrow soils.

cobbles on the surface; there are no bedrock outcrops. Surface boulders are plentiful, and it is possible to provide limited amounts of crushed rock and, with screening facilities, any desired gradation.

To date only a small portable crusher (capacity 25 cu yd per hour) has been available (Fig. 24), but it provided 1400 cu yd of crushed rock of various gradations (Fig. 25). This material was used experimentally as surfacing for roads and to construct test sections of roads on thin fills. Using the facilities at the Thule Air Base soil testing laboratory, a durability test, the Los Angeles abrasion test, was conducted on a specimen of crushed rock. A loss of 32% was measured, indicating an acceptable material for normal traffic, although on the soft side for heavy-load traffic.

Figure 24. Crushing boulders with portable crusher, capacity 25 cu yd per hour.

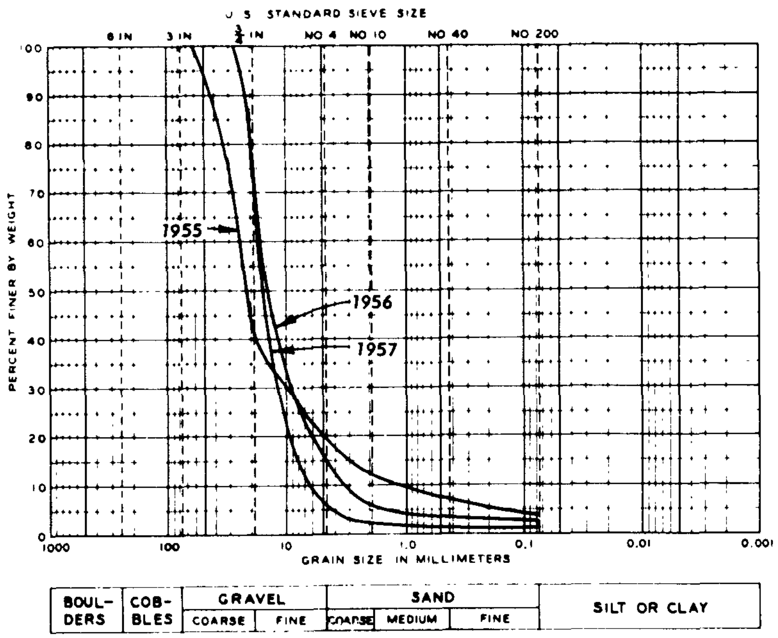


Figure 25. Typical gradations of crushed rock.

Steam-thawing of frozen soil

20. Steam has been used in the Arctic to thaw frozen ground for excavation and, in particular, to thaw a cylinder of ground prior to driving a pile. As this procedure had been quite successful, experiments were made to determine the feasibility of steam-thawing the permafrost in the TUTO area to determine if such techniques could be used to thaw sufficient quantities of material for use in earth construction.

Procedure. The source of steam was a tank-car heater of 3-car capacity (Fig. 26). It was supplied with water from a 500-gal tank (trailer type). A special connector was attached to the heater

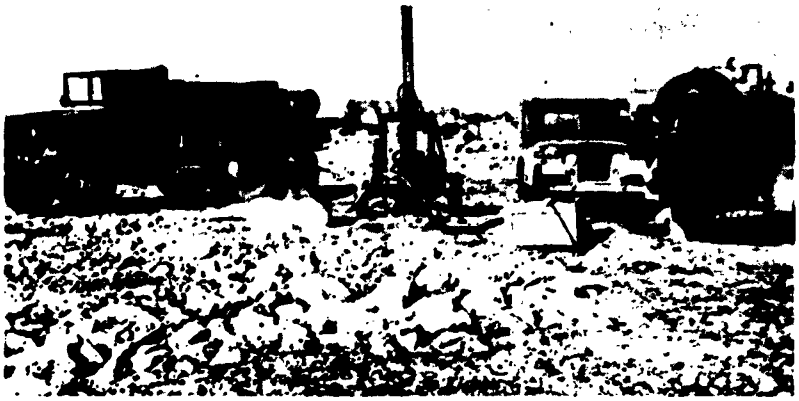


Figure 26. Test of steam-thawing of frozen ground. Tank-car heater for steam supply is shown at right center. Wagon drill for drilling holes in frozen ground to insert steam points shown in center (30 June 1956).

so that two lines could be attached. Standard 1-1/2-in. steam hose, and standard 3/4-in. steel pipe, with attached chisel-shaped points, were used. Two 1/4-in. holes were drilled in the points to permit passage of steam (Fig. 27). A suitable-size hole was drilled in the ground with a wagon drill, and immediately the point - with steam passing through it - was inserted in the hole. This procedure was necessary to prevent the hole from closing and refreezing. It was not possible with the apparatus at hand to maintain a constant steam pressure, and it varied as much as 50 psi. Two tests were conducted: three steam points were used in the first test, and four steam points in a 4-ft square in the second. This pattern was chosen because it would be practical to use if a large area had to be thawed. A thermocouple was placed in the center of the square to measure the heat flow.

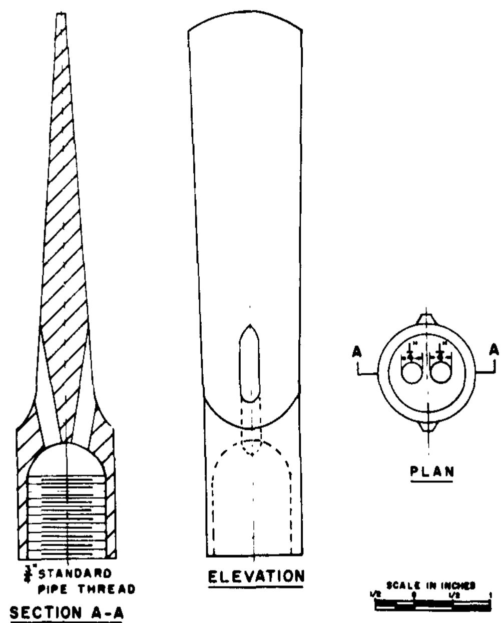


Figure 27. Steam point.

Test 1. The first test was conducted on 30 June 1956. Three steam points spaced 52 in. apart were inserted to a depth of 50 to 55 in. (about 15 to 20 in. was in frozen soil). A thermocouple was inserted in the center between the steam points (33 in. from each point) and at the same depth. Steam was run through the points at pressures

varying from 20 to 70 psi for 6-1/2 hours. At the end of the test, thaw had taken place in a 2-1/2-ft-diameter area around each point. The surface in each crater had sunk 14 in., and 6 in. of water was standing in the depression. The thawed soil was mud of the consistency of thick soup(Fig. 28). The thermocouple indicated practically no change in temperature and no thaw 33 in. from the steam points.

Figure 28. Thawing frozen soil with steam. The condition of the soil is shown after 6 hours of steam application (30 June 1956).

Test 2. The second test was conducted on 3 July 1956. Four points were installed, one at each corner of a 4-ft square, again to a depth of 50 to 55 in. A thermocouple was installed in the center of the square to a depth of 58 in. Steam was applied at pressures between 30 and 60 psi for 7-1/2 hours. Approximately 300 gal of water was used to provide the steam. Results from this test were exactly the same as for Test 1, and again there was no measurable rise in temperature at the thermocouple.

Results. The tests indicated that steam-thawing large areas by the above-described procedure would be uneconomical and impractical. In addition to requiring an excessive amount of heat energy, the injection of steam into the soil together with the melting of the ice in the soil created excessive amounts of water; therefore, extensive drainage and drying would be necessary before the thawed soil could be used as borrow material for roads or similar facilities. The "zero curtain" surrounding the steampipe sets a definite limit on the rate of transfer of heat into the frozen ground. In future studies of artificial thawing procedures, heat should be applied only in the amount necessary to maintain a reasonable rate of advance of the thaw boundary around the heating pipe, and much greater thawing time should be allowed. "Cooking" the thawed soil by forcing steam through it makes the soil unsatisfactory as borrow material because the cooking creates a highly liquefied soil condition; also, it is extremely wasteful of heat as it causes nearly all the thawed material to be heated to a temperature far above the melting point of ice.

Summary

21. The site of the investigations, TUTO, is a moraine adjacent to the edge of the ice cap, 1550 ft above mean sea level. The soil is predominantly unsorted glacial debris or till. Permafrost underlies the entire area, and the surface is generally covered with patterned ground.

Periodic measurements for three thaw seasons showed that the undisturbed ground thaws to an average depth of 39 in. The soil in this active zone was tested and found to classify as a silty sand (SM) with a dry density of 121 lb per cu ft and a water content of 10%. This soil description does not include the boulders and cobbles in the peripheries of the patterns.

Areas were found where the surface soil was either predominantly clean boulders and cobbles or sand. One area was found where patterned ground features were not pronounced and the soil was a clayey sand (SC).

Coarse-grained, frozen soil was successfully sampled by core drilling with standard drilling equipment using double-tube, swivel-headed core barrels and bottom-discharge, diamond-impregnated bits. The drilling fluid was cooled to below freezing temperature by the addition of snow and common salt. Some breakage and loss of cores were experienced to a depth of 10 ft, but full recovery and nearly perfect cores were obtained from the underlying cooler strata to a maximum depth of 62.3 ft.

Core drilling showed that permanently frozen overburden extends to at least the maximum drilled depth of 62.6 ft.

Tests on frozen cores extracted by drilling operations showed the top 7 ft of permafrost to be layers of sand (SP or SM), gravel (GP or GM), and silt (ML) with cobbles and boulders. The water content varied from 20 to 100% and dry density from 45 to 110 lb per cu ft. Water (ice) contents were greatest at the frost table and decreased with depth.

Below a depth of 10 ft, the permafrost was found to be a silty, sandy gravel (GP or GM) with an occasional layer of silty sand (SM) and frequent boulders. Water content varied between 3 and 13% and dry density between 128 and 145 lb per cu ft.

One drill hole showed a lacustrine deposit having alternate varves of silt, sand, and ice lenses to a depth of 29 ft. The material was generally nonplastic, but thin layers of clay occurred having a plasticity index between about 9 and 22. Below 29 ft, the soil was a silty, sandy gravel (glacial till) with boulders.

Subsurface temperatures were measured in two places to depths of 30 and 40.5 ft, respectively. The temperature remained nearly constant at about 10 F at a depth of 40 ft.

Suitable borrow materials for constructing gravel roads on the ice and ground areas were obtained within reasonable haul distances. Material from the active zone was scraped up and stockpiled with bulldozers.

The gravel roads on ice were constructed with a clean boulder and cobble fill that was more than 50% (by weight) cobble and boulder sizes. This material was found in areas where the surface had been washed by meltwater flow. A plentiful supply was found within 4 miles of the edge of the ice cap.

A silty, gravelly sand (SM) was used to surface the coarse material of the gravel roads on ice. Small borrow areas were located that were free of cobbles and boulders and contained a minimum of silt. Such areas were at random locations and were found by noting the absence of distinct pattern formations. An ideal, well-graded material for road surfacing was not found, and most of the material used was somewhat high in percentage of silt.

An abundance of soil was found over the entire area which, when stockpiled, was a bouldery till of 4% silt and 35% (by weight) cobbles and boulders. This soil was used for constructing roads on the ground and dikes and berms on the ice.

The available boulders were used to produce crushed rock in limited amounts. An abrasion test on a representative sample measured a loss of 32%.

A test was conducted to determine the feasibility of steam-thawing frozen soil. Steam points were inserted to a depth of 5 ft at each corner of a 4-ft square. The test showed that steam-thawing of the surface soils at TUTO by this procedure would be uneconomical and impractical. An excessive amount of heat energy is required and the melting of the ice in the soil, together with the injection of steam, creates excessive amounts of water. Before the thawed soil could be used as borrow materials for roads or similar facilities, extensive drainage and drying would be necessary.

V. MOVEMENT AND ABLATION OF THE SURFACE OF THE ICE RAMP

The Ramp

22. The TUTO Ramp is a sloping tongue of ice 1 mile wide with a relatively smooth surface as shown in the composite aerial photograph, Figure 29, and the maps, Figures 1 and 2. North and south of the ramp, the ice cap terminates in steep, shear, moraine formations. Still farther north and south it becomes a rapidly moving, rough-surfaced glacier. Thus, the TUTO Ramp provides a unique opportunity to reach the central ice cap from the ice-free land with surface vehicles. Reconnaissance by others [12,13] has shown other possible access areas, but none are quite as satisfactory as the TUTO Ramp.

Ablation and movement of the ice are constantly changing the profile of the ramp surface. In August 1957 the profile of the ramp was as follows: the first 3100 ft had a 6% slope; from 3100 to 3800 ft, a 4% slope; from 3800 to 5400 ft, a 5% slope; from 5400 to 11,000 ft, a 7% slope; and from 15,000 ft on, a 3.5% slope. The slope of the ramp is sufficiently gentle to allow almost any type of surface vehicle to ascend to the comparatively flat interior of the ice cap. The surface of the ramp is free of crevasses and other impassable obstacles; it can be traversed easily during the cold months when hard, wind-packed snow covers all irregularities of the surface and has sufficient strength to support oversnow vehicles without critical sinkage. During the thaw season (paradoxically, the time of year when weather, visibility, and similar factors are best for operations) the snow becomes wet and soft, and in low places it may become saturated and impassable even to low-ground-pressure vehicles. Channels as deep as 3 ft and as wide as 8 ft occur frequently; numerous ice hummocks are present, some of which are as high as 3 ft. When the snow cover has completely melted, the ice surface becomes rough as a result of erosion by meltwater streams, making travel difficult and slow for vehicles. The purpose of the road, therefore, is to provide passage over the rough portion of the ramp. As elevation increases, air temperature drops, thus decreasing the amount and intensity of snow and ice melting and thus ice ramp roughness.

The ice ramp at TUTO is a wedge of stagnant ice about 2000 ft long. During the thaw season, the winter snow cover melts and runs off in a network of small streams. As the thaw season progresses, the ice itself melts at the lower elevations, resulting in a steady lowering of the ice surface and retreat of the edge. These movements obviously present problems to construction of a semipermanent road on the surface. Moreover, similar movements can be expected at other locations on the margin of the Greenland Ice Cap or on any glacier-type sheet of ice. Accordingly, this investigation has included the measurement of the movement of the ice ramp.

Surface movement

23. Measurements of ice surface movement of the TUTO Ramp were commenced in 1954 under the direction of SIPRE [11] as part of an overall glaciological study of the ramp. Measurements were made by triangulation from a temporary base line. Base points were established on large boulders.

Figure 29. TUTO Ramp and vicinity, August 1956, approximate scale, 1:28,800.

Twenty-one points on the ice were triangulated for position several times during the months of July and August 1954. In 1955, as part of the Road Project (Project 1), the base points established the year before were reoccupied and eight points were located three times in the months of July and August.[6] The latter points were steel pins installed in the gravel fill of the roads constructed on the ice.

Although useful results were obtained from these early measurements, it was apparent that greater accuracy over a wider spread of points was needed. Many of the points were lost during the winter season, and movement of the base line from year to year was likely because of the frost action on the boulders marking the ends of the base line.

Base line and permanent base-point stations. In 1956, a new base line was established (see Fig. 2). The new line is 0.8 mile long and is situated to allow a clear line of sight from the stations (NN and SS) on each end of the base line over 2.5 miles of the 3-mile road on the ice. The base-point stations (Fig. 30) consisted of iron pipes placed in holes drilled by the core-drilling rig.

Figure 30. NN base point. The tripod is removable and is used to support a range pole (5 July 1957).

Figure 31 shows the construction details. In 1957, a third point (EE) was established to form a triangle with the original two points. It is planned to check the annual movement, if any, of the base points by triangulation and precise taping. The stations have also been used as bench marks, providing reliable reference points from year to year.

Movement measurements. In 1956, the movement of eight pins set in the road fill of the main Ramp Road and in the Transverse Road was measured. Of these, five had been used in 1955; others used in 1955 had been lost during road repairs. The pins were 1-in.-diameter, 2-ft-long, steel pins set vertically in the fill, the top about 6 in. below the road surface. This type of reference point was used in place of the usual pole set in the ice surface because it was considered more permanent. Poles set in ice rapidly melted free. (All poles used in 1954 were gone in 1956.) In 1957 three more

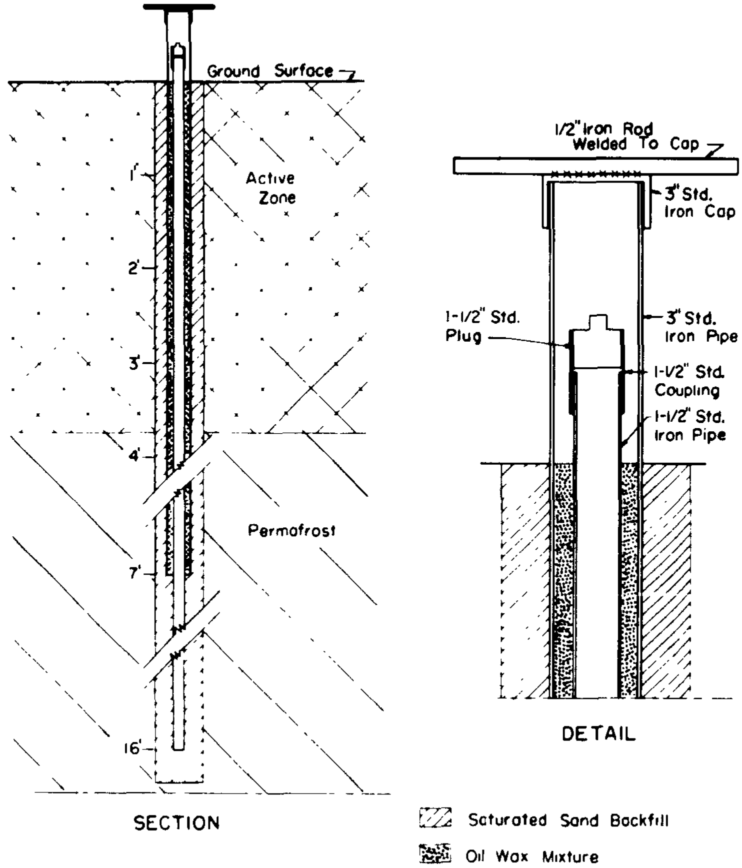


Figure 31. Example of permanent-type bench mark installation.

pins were set, making a total of 11. Other points from which movement was measured included points on five pile bents of the bridge constructed on the lower end of the Transverse Road, and the tubes set in ice in 1957 for the measurement of movement versus depth by means of an inclinometer.

Angles were measured with a theodolite, each angle being measured six times. All standard procedures were used to ensure maximum accuracy. When possible, all three points of the triangles were occupied; the error of closure was determined and balanced. For 90% of the measurements, the error of angle closure before balancing was less than 8 sec. An 8-sec error produced a maximum error in location of ±0.35 ft at a distance of 14,000 ft from the base line, the distance of the farthest point measured. Because of the orientation of points to the base line, the error may be considered as in the east-west direction. In actuality this error was greatly reduced by balancing the triangles. There were many days when poor visibility (fog or blowing snow) prevented work, and high winds frequently prevented work on other days. However, the occasional fine days of clear, calm weather were sufficiently frequent to permit three or four complete readings to be taken during the summer season.

Vertical movements were measured by leveling to the top of the reference pins. The accuracy obtained in measuring horizontal movement could not be maintained in measuring vertical movement because the continuous movement and ablation of the ice prevented maintenance of stable bench marks, and levels had to be carried 1 to 3 miles from the land area. Another difficulty arose in the middle of the 1957 thaw season when the weather was so warm that the ice beneath the road fills

melted slightly and the pins subsided with the fill. Thus some erratic values for the vertical movement of the ice during that period were obtained.

Results of measurements. A tabulation of all horizontal and vertical movements of the ice surface since the establishment of the new base line is given in Appendix B, Table B-V. The locations of measurement points are shown in Figure 2. Table VI lists the annual movement of those points for

Table VI. Ice Movement Measurements

Point	Period	Horizontal		Vertical	
		ft	Direction	ft	Direction
	Annual Movement, Ramp Road				
MP1	7 July 1956-10 July 1957	0.15	S53°05' W	0.16	Down
	21 Aug 1956-22 Aug 1957	0.19	S34°30' W	0.44	Down
MP66	7 July 1956-10 July 1957	6.92	N70°00' W	3.11	Up
MP8	7 July 1956- 9 July 1957	8.97	N75°15' W	2.13	Up
	20 Aug 1956-21 Aug 1957	8.71	N74°40' W	1.68	Up
MP10	24 July 1956- 9 July 1957	10.85	N75°45' W	0.67	Up
	20 Aug 1956-21 Aug 1957	11.21	N73°30' W	0.67	Up
MP14	20 Aug 1956-20 Aug 1957	11.17	N86°30' W	1.45	Down
MP15	20 Aug 1956-20 Aug 1957	8.85	S73°25' W	1.05	Down
	Annual Movement, Transverse Road				
MP7	7 July 1956-10 July 1957	2.04	N61°40' W	0.61	Up
	21 Aug 1956-21 Aug 1957	1.85	N63°40' W	0.67	Up
MP11	24 July 1956-10 July 1957	1.18	N52°55' W	0.24	Up
	21 Aug 1956-21 Aug 1957	1.03	N60°10' W	0.09	Up
MP13	27 July 1956-10 July 1957	0.88	N59°20' W	0.10	Up
	20 Aug 1956-22 Aug 1957	0.90	N53°05' W	0.34	Up
	Annual Movement, Bridge Bents				
B1	28 Aug 1956-22 Aug 1957	2.26	N70°35' W	NM	
B2	28 Aug 1956-22 Aug 1957	2.54	N61°50' W	NM	
B3	28 Aug 1956-22 Aug 1957	2.55	N58°50' W	NM	
B4	28 Aug 1956-22 Aug 1957	2.45	N54°35' W	NM	

Note: Location of points shown in Figure 2.
MP, movement pin in road fill.
B, bridge bent.
NM, no movement.

which measurements were available. These movements were computed from the position of points on dates approximately 1 year apart, and they do not represent the sum of individual short-time movements measured during the year. Although only 1 year of measurements is available, the pattern of surface movement may be seen from Table VI. Figure 36 (page 46) shows graphically the principal, measured, horizontal movements. Referring to Figure 2 for location of the points, the greatest horizontal movement occurs between MP8 and MP14 in the area of MP10, and is approximately 11 ft per year in a direction a few degrees north of west. Above MP 14 movement is slightly slower, about 9 ft per year, and slightly south of west. At MP14 vertical movement is downward, about 1.5 ft per year, changing to upward somewhere between MP66 and MP10. At MP66 maximum upward movement of

about 3.0 ft per year was measured; horizontal movement was slowed to about 7 ft per year. In the area below the intersection of the Transverse Road represented by MP1, both horizontal and vertical movements are very small. The record of short-time movements shows that MP1 moves erratically in all directions and at various speeds. It is sufficient to consider this section of ice as stagnant. Proceeding along the Transverse Road, the rate of movement decreases, although at the bridge, which is located on a relatively steep ice slope, the movement increases from 2.25 to 2.50 ft per year.

In Table VII, the horizontal movements of ice in feet per month have been computed. To date only a few points have been measured with sufficient continuity to allow the determination of rate of movement. Rates have been computed for the summer season (first to last location of points in work season) and for the winter season to allow comparison; however, accuracy is not possible because of the erratic movement. During any given short period, a point may move almost at right angles to its normal direction. In 1 or even 2 years of record, rates computed for comparatively short periods may

Table VII. Rate of Horizontal Ice Movement

Point	Road Station*	Rate of Movement, ft/month**			Average
		Summer 1956	Winter 1956-57	Summer 1957	
Parallel to Ramp Road					
MP1	13 + 35	0.091	0.012	0.045	0†
D11	19 + 40	NR††	NR	0.106	NR
MP17	27 + 10	NR	NR	0.711	NR
MP66	32 + 50	0.645	0.545	PR††	0.564
D10	33 + 50	NR	NR	0.750	NR
MP8	36 + 35	0.759	0.642	0.882	0.714
MP10	52 + 10	0.932	0.667	1.212	0.911
D14	54 + 20	NR	NR	1.670	NR
D12	66 + 00	NR	NR	1.441	NR
MP16	65 + 52	NR	NR	1.011	NR
MP14	101 + 43	NR	0.933	0.678‡	0.965
MP15	125 + 50	NR	0.827	0.366‡‡	0.762
Parallel to Transverse Road					
MP7	6 + 55	0.182	0.152	0.159	0.160
MP11	14 + 52	0.138	0.085	0.071	0.090
MP13	20 + 10	0.108	0.098	0.056	0.084
MP18	24 + 46	NR	NR	0.238	NR
D15A	24 + 38	NR	NR	0.189	NR
B1	Bridge	NR	0.184	0.287	0.189
B4	Bridge	NR	0.210	0.251	0.205

* Road stations are approximate, stations constantly change due to ice movement.

** Rate of movement computed as follows:

$$\frac{\text{Distance (ft) between location of points on selected dates}}{\text{Number of days between dates}} \times 30 \text{ days per month.}$$

† Moves erratically within a 0.5-ft-diam area, in all directions and at varying speeds.

†† NR, no record; PR, point removed.

‡ Moved erratically in southwest direction for 3 weeks. Rate of movement based on location at beginning and end of summer may not be representative.

‡‡ Same as 5 except moved southeast for 4 weeks.

not be representative. However, there is some evidence that rate of movement may be greater in the summer season than in the winter.* Several years of measurements will be necessary to establish reliable measurements and to obtain a quantitative comparison. The average annual rates of movement may be considered as of the correct order only. Again, several years of record are required to confirm the values.

The measurement of the position of pins at monthly intervals (see Appendix B, Table B-V) shows that individual points move horizontally in a zigzag manner, in the same general direction but deviating considerably in direction and amount in any one short period such as a month. It must be assumed, with no evidence to the contrary, that each point moves in the same irregular zigzag manner during the entire year. The actual path of each point throughout the year has not been determined, and the most significant value is the resultant movement in a year's time.

Subsurface movement

24. During the work season of 1957, a program of subsurface measurements of ice movement was instigated. The firm of Shannon and Wilson, Soil Mechanics and Foundations Engineers, Seattle, Washington, was engaged by WES to furnish an inclinometer, with necessary accessories, and the services of Mr. Stanley D. Wilson to advise and instruct on the use of the instrument and to assist in the analysis of the data collected. The inclinometer requires the use of a plastic tube with guiding grooves. The installation of the tubes in the ice was accomplished with a drill rig.

Eleven tube installations were made at various representative locations on the ramp. Three installations were made in holes approximately 200 ft deep, designated D10, D11, and D12. Their locations are shown in Figure 2. It will be noted that D10 is in the zone of upward movement, D11 is in the stagnant ice zone, and D12 is in the zone where movement is largely horizontal. The other installations were made in holes from 20 to 40 ft deep at locations selected to supplement the information from the deep holes.

A description of equipment and procedures, a summary of measurements, and a preliminary analysis of results are contained in a report by Mr. Wilson, which is included as Appendix C.

The measurement of subsurface ice movement has seldom been attempted, and there was little information available on procedures. The operation required careful planning, expensive equipment, and improvisation to adapt to unforeseen conditions.

Drilling. The experience gained in drilling frozen ground in 1956 was used to good advantage for the necessary drilling of ice. Substantially the same equipment was used except that, based on the previous year's experience, minor changes were made to adapt the equipment to the drilling of ice rather than frozen ground (Fig. 32). A special sheet-metal slush pan of 270-gal capacity, equipped with screens to filter ice and snow from the drilling fluid before it entered the intake hose, was used (Fig. 33). Several designs of hardened-steel bits were available for trial. Arctic-type diesel oil was used as a drilling fluid and was found to be satisfactory. As drilling was accomplished early in the season (May), it was usually not necessary to artificially cool the diesel oil. Moreover, no difficulty was encountered with melting of ice cores or icing in the hose lines. There was considerable snow on the ice during the drilling period, and it was necessary to remove the snow at each site in order to place the rig on a firm and nearly level surface.

* Measurements on Tako Glacier, Alaska, indicated a 10% increase in surface movement during the *winter* period. The increase was attributed to the accumulation.[3]

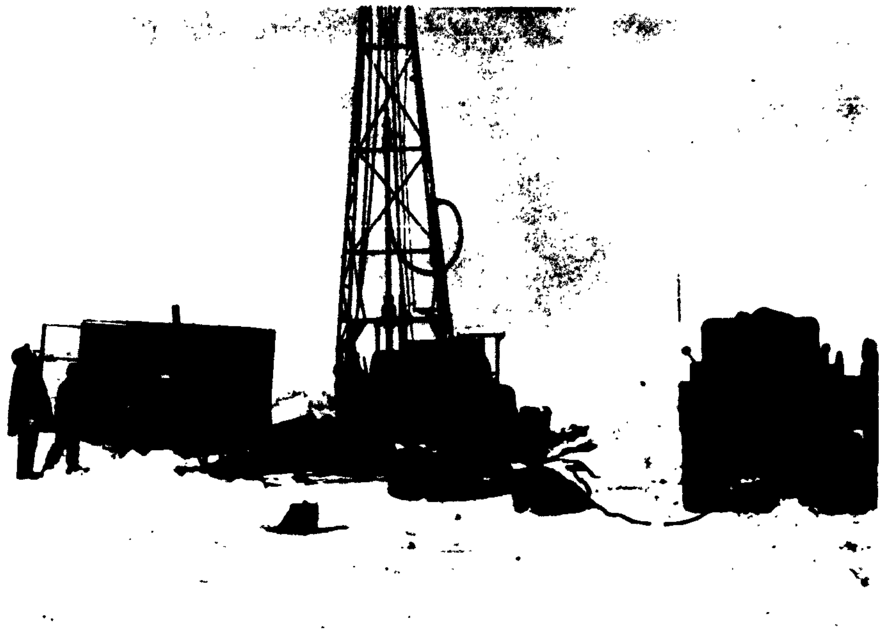
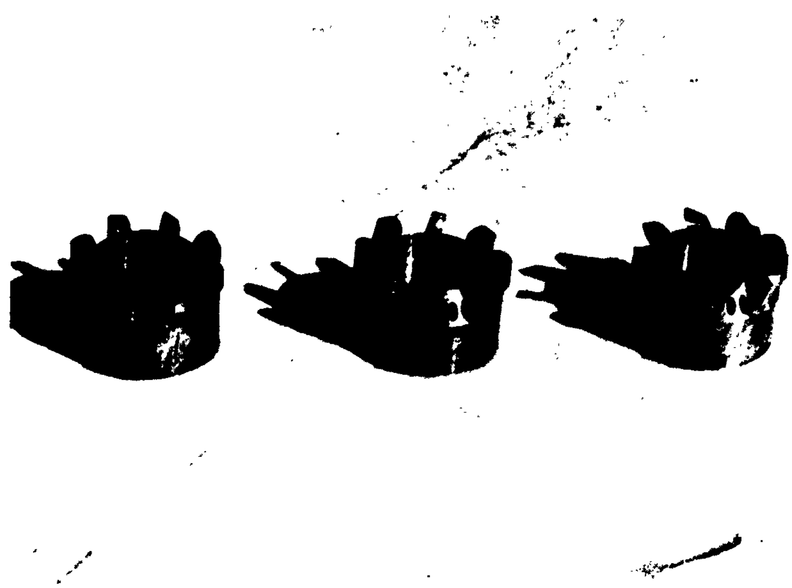


Figure 32. Drill rig drilling in ice to provide hole for plastic tube used to guide inclinometer. Truck-mounted compressor at right provided air for drilling initial hole to set casing. Core drilling commenced after length of casing was set.

Figure 33. Special slush pan used to contain drilling fluid (diesel oil). Note screens to prevent snow and ice from entering hose lines (4 May 1957).

Trials of various bits (Fig. 34a), drilling speeds, and other techniques resulted in loss of the core in the first 50 ft of hole D10. Thereafter, one bit, the fishtail bit shown in Fig. 34b, was used which worked satisfactorily; 100% recovery was usual, and excellent cores were obtained from the two other 200-ft holes (D11 and D12). All other holes were drilled with a noncoring, fishtail, hardened-steel bit.



a. Experimental bits.

b. Fishtail bit used successfully for coring.

Figure 34. Bits used for core drilling in ice (16 May 1957).

Installation of tubing. The tubes had to be frozen solidly and completely in the ice if their subsequent movement was to be truly indicative of the movement of the ice. In addition, the tubes could not be subjected to differential pressures of sufficient magnitude to compress them or the inclinometer would not pass through them.

The coldest temperature was somewhere between the surface and 50 ft below the surface. Thus there was a strong probability of water freezing between the tube and the side of the hole in this section before it froze at the bottom. This could cause either pockets of air around the tube or pressure on the tube if the water froze while confined. Therefore, the installation procedure was planned to promote freezing from the bottom of the tube upward. The following data were known:

Holes: Diameter, 5.75 in.
Total volume, 1.36 gal per ft.
Annular volume outside tubing, 0.88 gal per ft.

Tubing: Outside diameter, 3.34 in.
Inside diameter, 2.875 in.
Outside diameter of couplings, 3.87 in.
Weight, 1.16 lb per ft.
Inside volume to be filled with antifreeze, 0.34 gal per ft.
Volume of walls and couplings, 0.13 gal per ft.

Antifreeze: Specific gravity, 1.09; unit weight, 9.1 per gal.

Simultaneously, water was poured into the annular space around the tube and antifreeze inside the tube at rates such that the levels of water and antifreeze were always approximately equal. Using 55-gal drums and immersion heaters, both the water and the antifreeze were warmed to temperatures well above 32 F before they were poured. The antifreeze was always warmer than the water in order to slow freezing. In addition, an attempt was made to circulate warm antifreeze in the top 50 ft of the tube to slow freezing further.

Hole D10 was drilled first and the tubing installed (Fig. 35). In this case, the water was heated to 65 F and the antifreeze to 100 F. The installation was accomplished without incident,

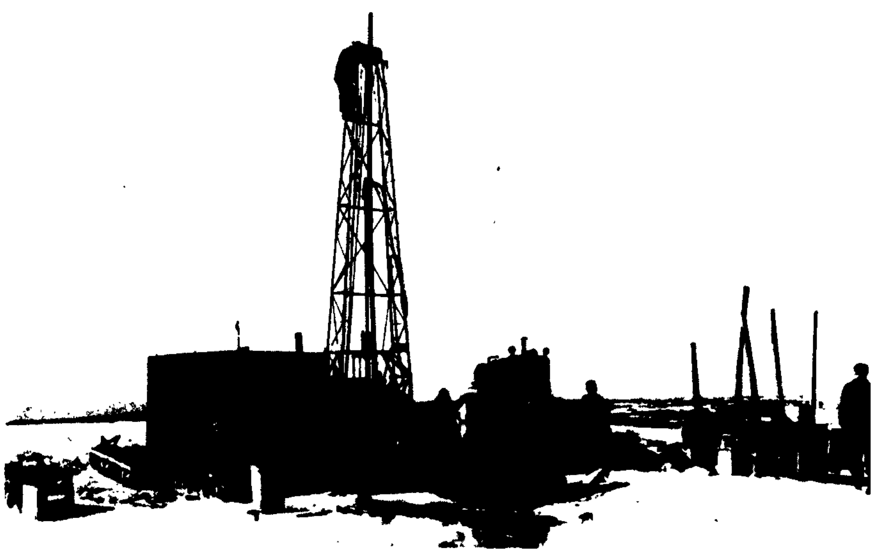


Figure 35. Installation of plastic tubing in drill hole, using hoist and tower of drill rig. Note battery of 55-gal drums with immersion heaters on right. These were used to heat water and antifreeze (17 May 1957).

except that cracking noises were heard from the tubing. Subsequently, it was discovered that the level of antifreeze in the tube slowly descended to 15 ft below the top of tube. It was concluded that temperature differences between the antifreeze, tube, and water were great enough to crack the tube and permit the antifreeze to leak out.

Hole D11 was drilled next and tubing installed. In this case, water temperature was 41 F and antifreeze temperature 46 F. Antifreeze at 100 F was circulated to a depth of 60 ft. There was apparently little or no cracking of the tube as loss of antifreeze was insignificant (1.1 gal). However, the first insertion of the inclinometer showed an obstruction at 97 ft. Subsequent measurements with an improvised measuring device showed a gradual constriction starting at 54 ft and ending at 111 ft, with the smallest diameter between 2.25 and 2.50 in. The reason for the constriction has not been definitely determined. The ice in this area is practically stagnant, and it is unlikely that there would be sufficient pressure from the ice movement to effect a closure of the tube, particularly in a few days. So far as is known, there was no cracking or breaking of the tube sufficient to weaken the tube strength at the point of constriction. It appears likely that, in spite of all precautions, the tubing froze to the ice at a relatively shallow depth, and that excessive external pressures were developed during the subsequent freezing of the underlying entrapped water.

Hole D12 was drilled and tubing installed on 27-30 May 1957, the last of the 200-ft holes. During placement of tubing in the hole, a coupling failed and 120 ft of tubing dropped to the bottom of the hole. The tubing was recovered, using a core lifter with the drill rig, and the remainder of the installation was accomplished without mishap. Water temperature was 50 F and antifreeze temperature was 60 to 65 F. Warm antifreeze was circulated for a short time in the upper 50 ft of tubing, but equipment difficulties prevented the continuation of circulation operations. A few days after installation, the tube was found to contain slush ice to a depth of 60 ft. Apparently, cracks existed in the tubing at depths of 40 to 60 ft and allowed the antifreeze to leak out. Cracks in the upper 10 to 20 ft of tube allowed water to seep in. It was frequently necessary to melt the ice in all the tubes after their installation.

In the 20-ft- to 40-ft-deep holes tubes were installed without difficulty.

Measurements. The instruments and procedures used to measure ice movement are described in Appendix C. After some initial failure of the wiring system the inclinometer performed very well, and it proved to be a satisfactory instrument for the unique purpose to which it was put. A hand winch mounted on a wooden stand was added to the original equipment for use in raising and lowering the inclinometer.

In the first year, it was necessary to commence measurements in each tube as installation was completed. Furthermore, the measurement of surface movement, by survey triangulation, could not be properly timed to correlate directly with the inclinometer measurements. The measurement of total vertical movement of each tube by survey leveling was not accomplished in time to give direct values for the season. Interpolations and extrapolations were necessary to reduce the available data to correlating time periods. These difficulties can be corrected, to a considerable degree, in the next year of measurements, but the 1957 measurements suffer, to some extent, for this reason.

Summary of results. The analysis of the results of the brief (3 months) period of record required some assumptions and extrapolations to complete the data. In his report (Appendix C), Mr. Wilson accomplished this admirably with the information he had at the time of writing. Subsequent measurements and analysis have confirmed that the results presented in Appendix C, Figures C8, C11, and C15, are approximately correct and can be discussed with confidence. However, as discussed for the surface movement measurements (paragraph 23) too much reliance should not be placed on short-time measurements of ice movement, because of the tendency for erratic, jerky motion. In a period of 3 months, movement was small, possibly in some cases less than measurement error. However, some

trends are evident which are important considerations in the construction of various facilities on the ice. They are:

a. The results of measurements in hole D11 confirm the conclusion that for all practical purposes the ice in this area is stagnant. Differential movement with depth, both horizontal and vertical, is very small and erratic in direction.

b. Measurements in hole D12 indicate that there is very little, if any, differential movement, either horizontally or vertically, in the top 200 ft of ice. At the hole D12 level, surface horizontal movement was greater than at any other level on the ramp.

c. At hole D10, horizontal movement is about 17.5% slower at a depth of 200 ft than at the surface. There is also a significant differential upward movement in the top 200 ft, as measurements indicated a stretching or elongation of the tube. The shape of the curve of a plot of horizontal and vertical movement versus depth indicates that movement at the ice-soil interface (approximate depth 400 ft) is very small or, possibly, zero.

All measurements of movement with depth indicate that there is little or no differential movement in the top 50 ft of ice. Thus, piles or other structures inserted in the ice to depths of less than 50 ft would not tilt because of ice movement.

Crack survey

25. *Procedure*. In late August 1957, a survey was made of the pattern of cracks on the ice surface of the ramp (Fig. 36). Location of cracks was by stadia distance and angle, using the reference points in the road fills which are located at intervals for movement measurements ("MP" points). The cracks were classified by visual inspection into three categories - compression type, longitudinal type, and shear type - depending on their orientation to the direction of thrust. Although these names are used for convenience of identification, they should not be assumed to necessarily express the actual stress conditions at the surface of the ice. For example, the "compression" cracks in the zone of upthrust just upslope from the zone of stagnant ice are, as illustrated in Figure C17, Appendix C, actually in a zone of upward bulging where the surface is being subjected to extension and/or upthrust shear. Further, many of the cracks may be a reflection of distortion caused by irregularities of the underlying topography as the ice moves over it, or may be the result of temperature stresses in combination with stress patterns produced by the other causes.* Possibly, also, the cracks may be influenced by residual crack patterns persisting from times when the ice was somewhat farther from the edge and was stressed very differently.

Results. The pattern of cracks as determined by the survey is shown in Figure 36 together with the surface contours (more detailed surface contours are shown in Fig. 2) and the average annual movement of the points in the road fills for the year 1956-1957. No cracks are shown past Station 70+50 on the road because snow and slush covered the ice surface and the cracks could not be discerned, although it is probable that the cracks continued in somewhat the same manner as before Station 70+50. Figure 36 shows that past Station 50+00 on the Ramp Road, the cracks are the shear type, oblique to the direction of thrust. A bend in the alignment can be noted next to the moraine formation, probably indicating a change in direction and rate of movement as would be expected. Also, there is a bending away from an area around the 1800-ft contour to the south of the road. Apparently some erratic movement occurs in this area, although the measurements to date have not shown its nature or cause. The crack pattern clearly indicates the zone where the movement measurements show a change to upward and a slowing of the horizontal movement before reaching the stagnant ice.

* Assuming a linear thermal coefficient of expansion of 0.000028 (per °F), cooling of a layer of ice by 40 F, from 32 F to -8 F, would cause a contraction of about 1-1/3 in. per 100 ft. The maximum width of cracks from this cause should occur in the spring (March-June).

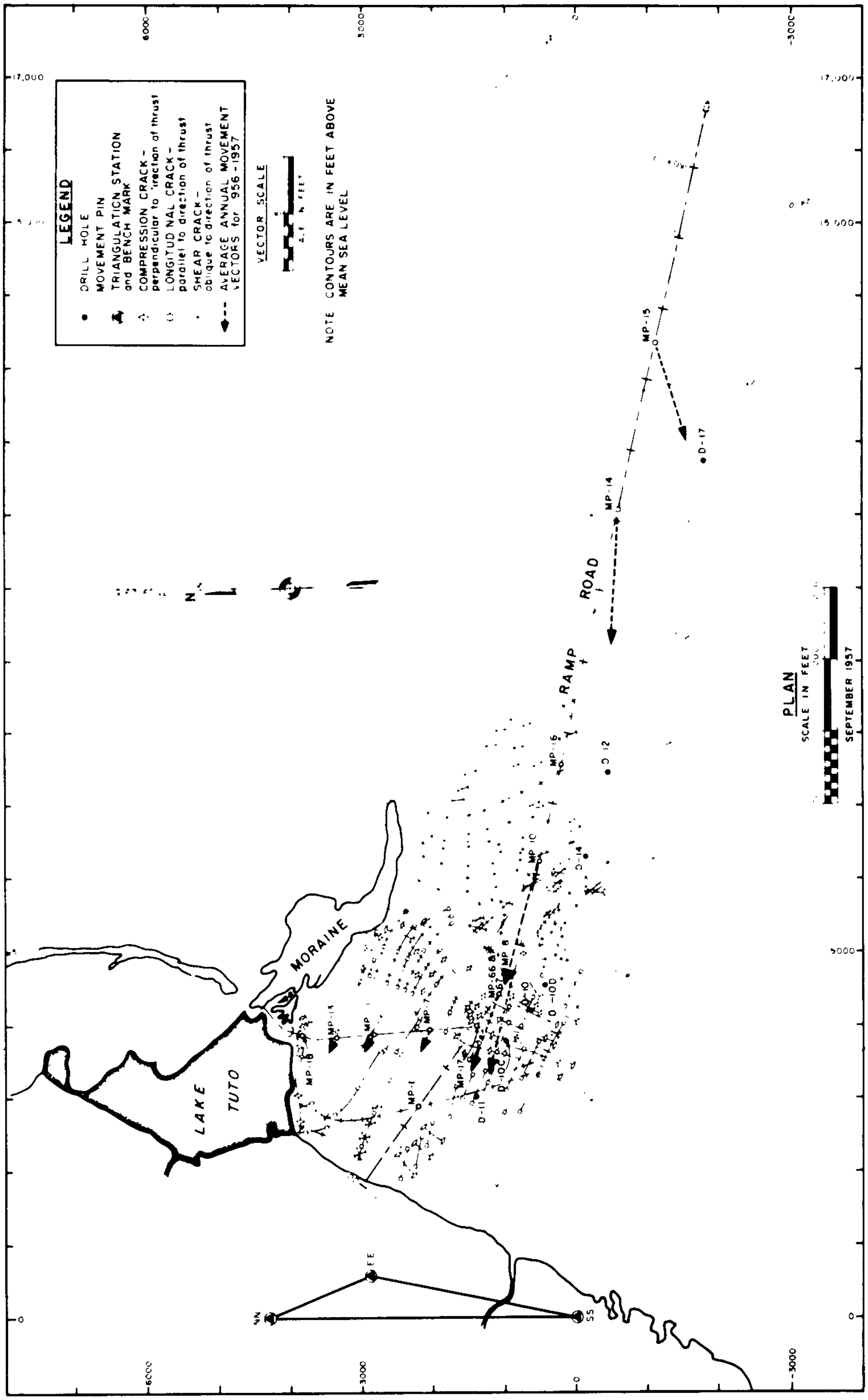


Figure 36. Movement and crack pattern, TUTO Ramp.

Compression-type cracks (perpendicular to the direction of thrust) are frequent and closely spaced (Fig. 37). Longitudinal cracks are also frequent and closely spaced, crossing the compression cracks. Running through the center of this zone of closely spaced cracks are the so-called "hummocks," knobs of hard, blue ice, sometimes 2 to 3 ft high. Below this zone of intense activity the cracks are generally few, erratically located and aligned. A long shear crack runs diagonally across the road at MP1, possibly indicating a change in direction of movement. The crack pattern appears to correlate directly with the movement and can be considered an indication of the type and direction of the movement.

Figure 37. Cracks in ice surface in area north of Ramp Road and west of Transverse Road (10 Aug 1957).

The cracks are sometimes open (Fig. 38), but frequently they are filled with ice to within a few inches of the surface. It has been suggested that the opening and closing of cracks and the expansion and contraction of ice with temperature may affect the overall movement. However, measurements of movement with depth indicate that rate of movement remains relatively uniform for more than a depth of 50 ft. Therefore, it is probable that the effect of temperature on the ice surface is small, as far as overall movement is concerned, although it may be the cause of some of the eccentricity of short-time surface movements.

Figure 38. Close-up of typical crack in ice surface (5 June 1957).

Figure 36 shows that there is a relation between direction of surface movement and the surface contours or direction of slope. Direction of movement is approximately perpendicular to surface contours or in a downslope direction. There is also an indication that the steeper the ice surface slope, the more rapid the movement.

Ablation

26. At the beginning of the thaw season, the ice ramp is covered with snow. Snow depth varies from year to year (see paragraphs 11 and 12), but normally is 4 to 5 ft in the first 1/2 mile, decreasing to 2 to 3-1/2 ft at the end of road at Mile 3 (Fig. 6). As the thaw season progresses, the snow melts. In an average season the snow on the ramp melts completely, exposing the ice surface on the first 9000 ft of ramp. Above this area, at least to the end of the road at Mile 3, the snow cover partially melts, and only in an exceptionally warm summer (e.g. 1957) does it completely melt and allow an appreciable ablation of the underlying ice. At any given point the amount of ice lost in a thaw season varies, depending on (a) the depth of snow cover at the start of the thaw season and (b) the air thawing index and the net radiation reaching the surface for the season.

On the TUTO Ramp, a third factor is introduced in that the presence of man-made gravel roads has resulted in dust and soil debris on the ice surface; the intensity of ice melt varies with the degree of concentration* of dirt on the ice. An increasingly larger area of ice has been affected by dust and soil debris since the initial construction of the roads.

All of the three factors listed above vary, depending on a fourth factor: the location on the ramp. Figure 6 shows that the snow cover varies considerably proceeding up the ramp. Table V shows that the thawing index decreases rapidly with increasing elevation. The quantity of dust and soil debris is greatest in the first mile of ramp because this section of road was constructed first. The last mile of Ramp Road was not constructed until 1956. There are, therefore, four factors profoundly affecting the amount of ablation of the ice: (a) snow cover, (b) air thawing index and radiational heating, (c) dust and soil cover, and (d) location on the ramp with reference to relative elevation.

Measurements. Since 1955, the ablation of ice adjacent to the road has been measured by survey cross sections across the road and extending 500 ft or more on each side. Usually three sets of sections were obtained in a summer at Stations 13 + 00, 36 + 49, 52 + 30, and 155 + 00 on the Ramp Road. Figure 39 shows selected cross sections which indicate the amount of ice ablation in a year. The road stations indicated are only approximate because the horizontal ice movement continuously shortens the road and stations change. Likewise, true elevations cannot be used because of the vertical movement. The sections are shown as if there were no vertical movement of the road.

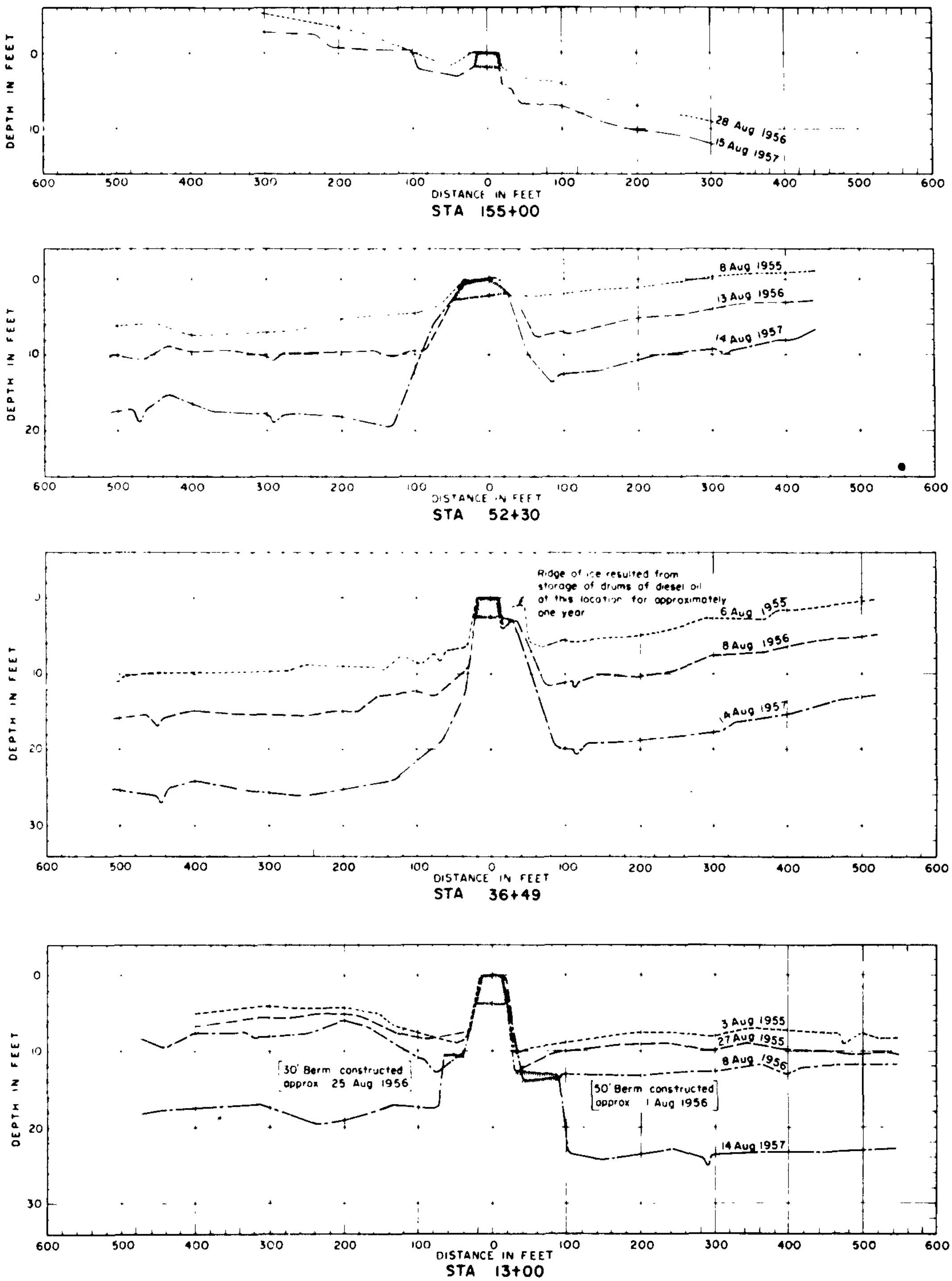
In the 1957 season, the Signal Corps Meteorological Detachment measured the rate of snow and ice ablation at Met. Station 2, 1 mile from the edge of ice, and at Met. Station 3, 3 miles from the edge of ice. Measurements were made daily, resulting in an excellent record of the rate of ablation for the 1957 summer season. The results are shown in Figure 40.

After the inclinometer tubes were installed for ice movement measurements, a program was commenced to measure the height of the snow or ice surface from the top of tube.

Results. Table VIII is a summary of annual ablation of ice in the years 1956 and 1957 compiled from: (a) values of the average thickness of ice between cross sections in Figure 39, (b) values measured at Met. Stations 2 and 3, and (c) values obtained from measurements on the inclinometer tubes.

It is apparent that the quantity of ice lost can vary greatly from year to year. Probably the greatest factor influencing this variation is the heat available from solar radiation and air temperature. The air thawing index is an indication of the heat available from the air temperature. As

* Laboratory experiments indicate that the maximum rate of melting occurs when the thinnest possible layer of a given soil completely covers the ice. (See reference 6.)



NOTES

(1) Stations refer to Ramp Road stationing (see Fig 2)

(2) Movement of the ice beneath the road results in upward or downward movement of the road surface. To show the correct relation of top of road to top of ice surface, the center line of the road has been assummed to remain at the same elevation.

(3) Road stations listed were true stations at the close of the 1955 thaw season. Horizontal movement of the ice results in constant shortening of the road.

Figure 39. Ice ablation cross sections, TUTO Ramp Road.

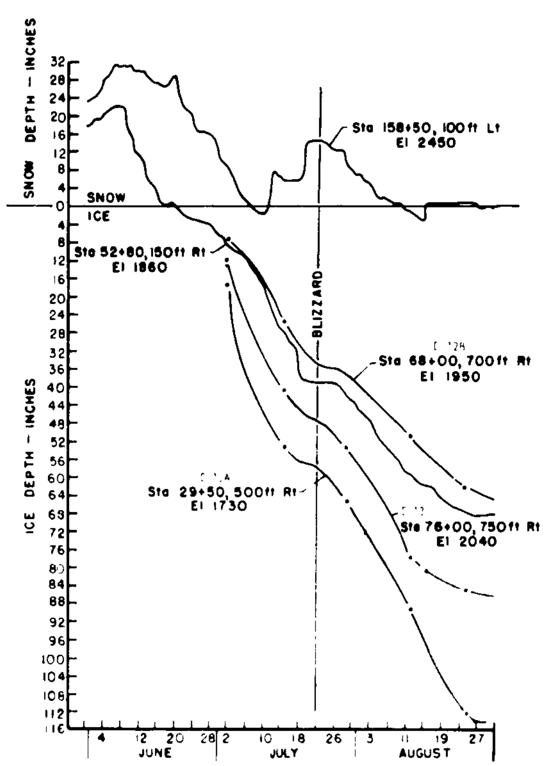


Figure 40. Rate of snow and ice melt, TUTO Ramp, 1957.

shown in Table V, the air thawing index for 1956 at Met. Station 2 was 238; for 1957 it was 427, a ratio of 0.55. Thus, the ablation of ice in 1956 might be expected to be a little more than half that of 1957. Other factors affect the relation, however. The year 1956 was characterized by a heavy snow cover, particularly on the first mile of the ramp. This situation is reflected in a smaller amount of ablation at Station 13+00 than at Station 36+49. In 1957, with a shallow snow cover, the melt at Station 13+00 was greater than at 36+49. In the same season, there can be local variations in the amount of ice ablation where snow has drifted and remains late in the season, protecting the underlying ice from melt. In other areas (an example is the hummock area) the snow is almost completely blown from the surface of the ice and the ice melts rapidly, commencing early in the season.

Table VIII shows the decrease in ablation with increase in elevation on the ramp. It will be noted that there was no ice melt in 1956 at the end of the road. In 1957, there was an average of 2.5 ft adjacent to the road, as shown by the cross sections in Figure 39, but at the Met. Station only 0.4 ft was measured, as shown in Figure 40. The reason for this apparent discrepancy is the amount of dirt on the snow or ice surface. At the Met. Station, every effort was made to keep the area clean and free from debris of all sorts. Adjacent to the road, the ice surface became quite dirty from blowing dust and from soil debris spread over the area by meltwater flow.

Table VIII. Ablation of Ice, TUTO Ramp

Station	Elevation ft msl	Ablation of Ice, ft		Remarks
		1956	1957	
13+00	1645	4.0	10.0	Average thickness 500 ft each side of road
21+00	1664		11.3	Record from inclinometer tube D11B
29+50	1730		9.4	Record from inclinometer tube D10A
33+00	1759		10.3	Record from inclinometer tube D10
36+49	1790	5.0	9.3	Average thickness 500 ft each side of road
52+30	1870	4.5	6.5	Average thickness 500 ft each side of road
52+80	1860		5.7	Daily measurement at Met. Station 2
68+00	1950		5.2	Record from inclinometer tube D12B
76+00	2040		7.1	Record from inclinometer tube D13
155+00	2440	0.0	2.5	Average thickness 500 ft each side of road
158+00	2450		0.4	Daily measurement at Met. Station 3

Recession of glacier. A net result of the summer ablation of ice and the lack of forward movement of ice at the edge is a recession of the ice edge. On 10 July 1957, a series of 10 reference stakes was established, designated IC1 to IC10, inclusive, and located as shown in Figure 2. Distance to the edge of ice from each stake was measured periodically.

Table IX shows that the ice receded an average of 41 ft in two-thirds of the 1957 thaw season. As 1957 was an unusually warm year, it is probable that this amount is greater than normal. Several more years of record are required to determine the average rate of recession.

Table IX. Recession of Glacier

Reference Stake*	Distance to Edge of Ice, ft		Amount Receded ft
	26 Aug 1957	10 July 1957	
IC1	90	43	47
IC2	72	44	28
IC3	93	56	37
IC4	82	49	33
IC5	89	46	43
IC6	59	35	24
IC7	103	63	40
IC8	121	63	58
IC9	112	65	47
IC10	110	58	52

* See Figure 2 for location of reference stakes.

Effect of movement and ablation on the ice surface

27. The life expectancy of roads on the ice ramp depends primarily on the rate of movement and ablation of the ice. Figure 41 shows the long-time effect of these two factors on the ice and road surfaces. The road surface profile and a profile of the adjoining (400 ft south) ice surface for 1957 are shown. Based on the direction and amount of annual movement measured for the year 1956-1957 and the average annual ablation for the years 1956 and 1957, projected profiles for the road and ice surface after 10 years are shown. The period of 10 years has no special significance; it was chosen for convenience in computation and plotting.

The profiles of the ice surface shown in Figure 41 indicate that the slope of the first 2 miles of ice will steepen in 10 years from an average slope of 6.6% to approximately 7.1%, and the edge of the ice will recede about 600 ft. The trend is toward an increasingly steeper slope, and after many years the ice may terminate in a steep, clifflike face. With faster rate of flow of ice as the surface steepens, it is conceivable that the ramp might become an actively calving glacier, dumping ice into the little valley now containing Lake TUTO and, as shown by seismic measurements, extending under the ramp. If the present trend is continued, the ice ramp will eventually be too steep for construction of a road for wheeled-vehicle traffic, but this will not be the case for at least 25 years.

The foregoing conjectures concerning the future of the ice ramp must be qualified in that they apply to the existing ice which has a more or less dirty surface. If the ice surface were clean the trend might be the same, but the time to accomplish the same results would be greater.

There is also a possibility that the upward movement of ice in the hummock area is depositing soil on the surface and will eventually form a moraine similar to the natural moraine north of the ramp. However, the amount of annual deposition is certainly small and is obscured by the dirt from

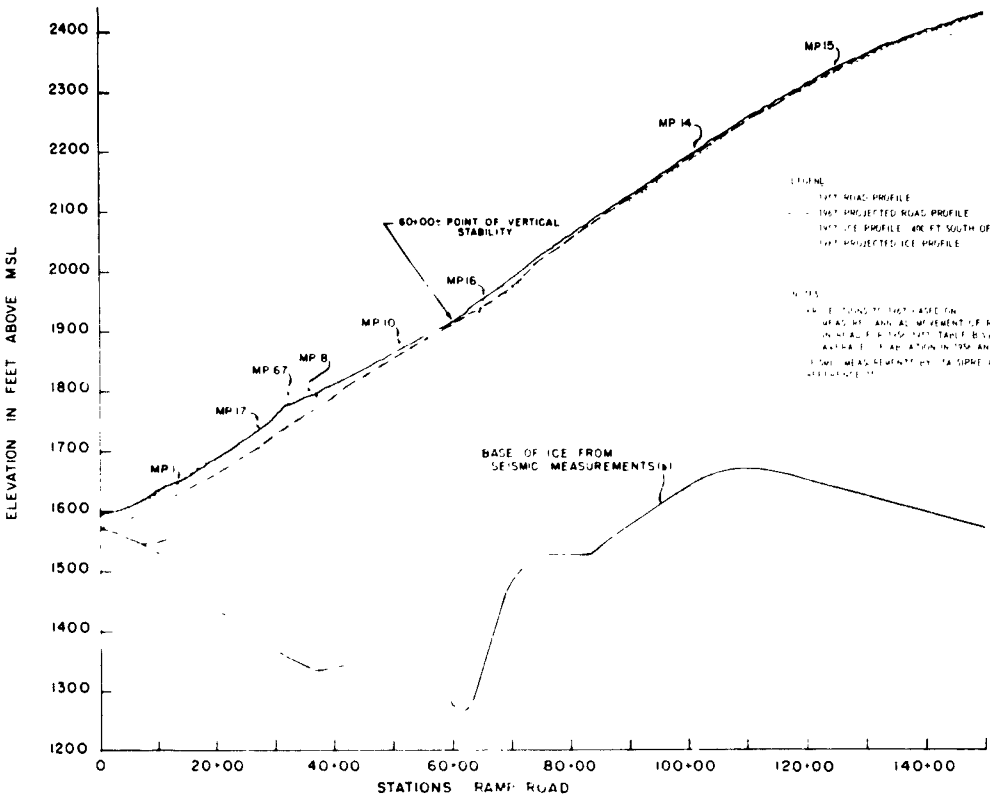


Figure 41. Profile, TUTO Ramp Road, present and projected 10-year position.

the road. Discolored ice bands are present and clearly discernible; however, no significant bands of soil have been observed, and it is probable that moraine formation will be very slow, requiring hundreds of years.

Meltwater

28. The melt of snow and ice during the thaw season described in paragraph 26 obviously creates a quantity of water. This water runs off the ice ramp in a network of channels eroded in the ice surface (Fig. 42). Normally, all these channels terminate at the edge of ice, in a small stream, or in Lake TUTO. In general, the principal channels recur every year, following the configuration of the surface. The construction of roads on the ice surface tends to disrupt the natural pattern of channels. When a road such as the Transverse Road crosses the normal flow direction, the water is intercepted and redirected unless provisions are made to carry it through the road. The construction of the Ramp Road divided the ramp drainage area into two sections: (a) the south section which is unrestricted and drains freely, and (b) the north section whose drainage is restricted to the area between the Ramp Road and the moraine formation on the north. The Transverse Road cuts across the north section, intercepting all flow and redirecting it toward Lake TUTO at the landward edge of the moraine.

The quantity of meltwater flowing from the ramp in a thaw season varies, depending on the same factors discussed for the ablation of ice (i.e. snow cover, thawing index and radiational heating, and amount of soil and debris on the ice). However, all snow and ice melted in a thaw season does not run off as meltwater. When a deep snow cover remains long on the very cold ice, the

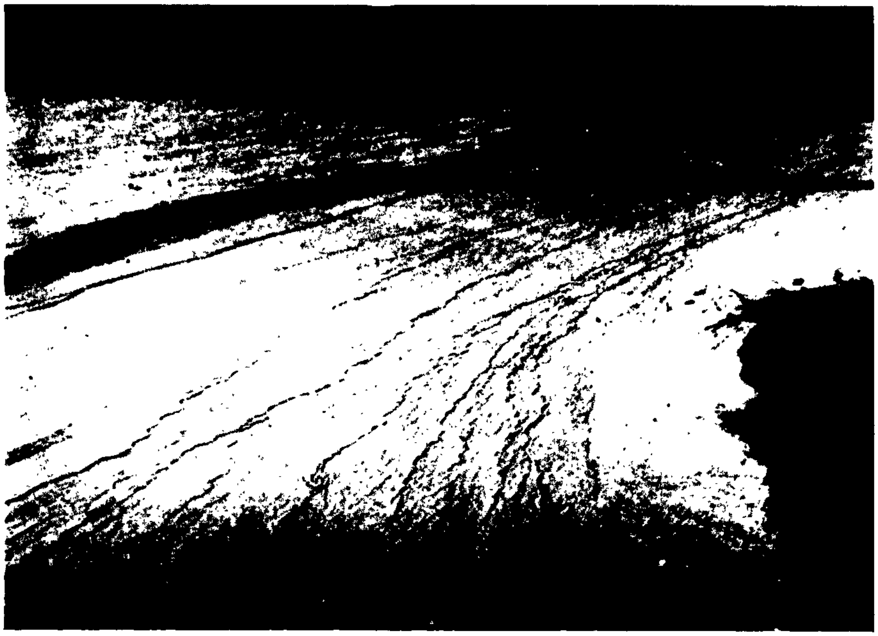


Figure 42. Meltwater channels eroded on the ice ramp (Aug 1957).

meltwater resulting from melting snow at the surface tends to freeze when it reaches the ice surface, forming "superimposed" ice. If the thaw season were sufficiently short or cool, this ice might never melt and there would be a net gain in ice rather than a loss. On the TUTO Ramp (out to approximately 2 miles) this is normally not the case; nevertheless, the meltwater runoff is undoubtedly less than would be indicated by the quantities of snow and ice melted in a season. Dr. Schytt[7] estimated, on the basis of core borings in the ice, that as much as 12 in. of superimposed ice could remain on the ramp after an unusually cool summer, if there were a very deep snow cover the previous spring. Therefore, the correlation between ablation and meltwater runoff is not easy to calculate, and extensive measurements are required to establish a reliable relation. No attempt was made in 1956 or 1957 to measure total runoff or to make a complete study of the problem; the requirement was noted for future study.

Since 1957 was an unusually warm season, quantities of meltwater far exceeded those previously observed. Maximum flow occurred during the first week in July when the sun's angle with the horizon was greatest. This condition combined with the warm air temperatures resulted in a maximum rate of melting. The flow in the channels varied considerably during a 24-hour period, reaching a peak between 1:00 and 3:00 p.m. and diminishing substantially at night. Other conditions affecting the rate of flow are the degree of cloudiness and the velocity and direction of wind. A maximum flow of 500 cfs occurred in the channel beneath the bridge on the Transverse Road. This flow represents a large portion of the runoff of an area of approximately 1000 acres. The remainder of the runoff was carried in the two or three culverts through the Transverse Road that were still functioning. In 1957 the meltwater channels began to freeze on 15 August; thereafter, flow decreased rapidly.

Summary

29. The TUTO Ramp is a smooth-surfaced tongue of ice, with a slope of from 4 to 7%, rising from the ice-free land area.

Measurements of the surface movement of the first 2-1/2 miles of ice were made, using

triangulation based on a line established in 1956. Base points that are not affected by freeze and thaw action of the surrounding soil were constructed at each end of the base line.

In 1956 and 1957, horizontal movement of the ice surface was 11 ft per year opposite Station 52+00 on the Ramp Road, 9 ft per year at Station 125+00, 9 ft per year at Station 36+00, and zero at Station 12+00. Direction of movement was downslope, at right angle to the contours. Vertically, the ice moved downward above Station 60+00 at least to Station 158+00, the maximum measured amount being about 1.5 ft per year. Between Stations 21+00 and 60+00, the ice moved upward; the maximum movement was 3.0 ft per year at Station 32+00. Below Station 20+00, the ice moved only 0.2 ft per year and movement was erratic in direction.

Measurements of subsurface ice movement were accomplished with a special slope inclinometer. It was used to observe the movement of wells, i.e. plastic tubing frozen into place in holes drilled in the ice. Eleven such wells were drilled; three of them were 200 ft deep. A special procedure was used to freeze the plastic tubes in the ice, to prevent contraction of the tubes, and to ensure continuous contact between the tubes and ice. This consisted of simultaneously pouring warm water into the annular space around the tubes and warm antifreeze inside the tubes. In general the procedure was satisfactory, but in one instance a tube was pinched so that the inclinometer would not pass through it. Difficulty was also encountered with cracking of the tubing, presumably because of temperature differentials.

The core from hole D11A, located 1800 ft from the edge of ice, showed 190 ft of ice over frozen moraine material (silty, sandy gravel with boulders). The moraine material was successfully cored to a depth of 49 ft.

Measurements made during the thaw season of 1957 showed very little, if any, differential subsurface ice movement in holes D11 and D12. No appreciable elongation of the tube was detected at either hole.

In the hummock zone (hole D10) the ice moved horizontally and upward; there was a slowing of the rate of movement with depth both horizontally and vertically. The rate of horizontal movement was approximately 17.5% slower at a depth of 200 ft than at 50 ft. The rate of upward movement decreased approximately 60% at the 200-ft depth. Extrapolation of the curve of a plot of movement versus depth suggested that there was little to no movement at the ice-soil interface, a depth of 400 ft.

Differential horizontal movement in the upper 50 ft of ice was not significant.

The surface of the ice ramp is covered with cracks ranging from hairline to several inches in width. A survey of the crack pattern showed that where movement was primarily horizontal, cracks were approximately evenly spaced and slightly oblique to direction of thrust. Where movement was strongly upward, cracks were closely spaced in a checkerboard pattern perpendicular and parallel to direction of thrust.

On most of the TUTO Ramp (at least for 3 miles), ablation of ice occurred during the thaw seasons when measurements were made. The amount varied from year to year, depending on the temperature regime and the depth of snow cover. In 1956, ablation of ice was 4 to 5 ft in the first mile, decreasing to zero at 3 miles. In 1957, ablation was 10 to 11 ft in the first 3/4 mile, decreasing to 0.4 ft at 3 miles. Variation of as much as 2 ft occurred in these zones, depending on the degree of concentration of dirt on the ice surfaces and on local differences in snow cover. The edge of the ice receded more than 41 ft in the 1957 thaw season.

The melting of snow and ice during the thaw season creates a network of meltwater streams on the ice ramp. In 1957 flow was greatest during the first two weeks of July, and it fluctuated from

day to day depending upon weather conditions. The amount of flow also fluctuated in a 24-hour period, usually reaching a peak at about 2:00 p.m. Maximum flow from the area between the Ramp Road and the moraine formation to the north exceeded 500 cfs.

VI. THAW OF SOILS AND MELT OF ICE

30. Thawing of frozen ground and melting of glacier ice are major factors to consider in the development of criteria for construction of roads in high-latitude regions, particularly in the TUTO area. The more important thaw and melt problems encountered at TUTO can be summarized as follows:

a. The settlement or subsidence resulting when perma ›st containing ice in appreciable amounts thaws. This situation may occur when roads, foundations, and similar structures are placed on permafrost in such a manner that the natural thermal regime in the soil is disturbed.

b. The softening, subsidence, and sloughing of gravel fills on ice resulting from melting ice beneath and adjacent to the fills.

c. The direction and disposal of meltwater to prevent damage to structures erected in the area.

These problems are not peculiar to the TUTO area; they are common to areas having similar terrain and climatic environments. Solutions developed for the TUTO area will, therefore, have application in many arctic construction problems.

Before methods can be developed to prevent the detrimental effects of thawing soils and melting ice, the extent of each must be measured. Such measurements were accomplished as a part of this project. The melt of ice on the ice ramp was described previously in paragraph 26; the measurement of thaw of frozen ground is described in the following paragraphs.

With a sufficiently long record of thaw depth and ice melt it is possible to develop methods for estimating quantities of thaw depth and ice melt. However, these predictions can apply only to the area in which the measurements were made because of the close relation of weather characteristics, soils types, terrain features, and other factors which vary from area to area. Accordingly, the scope of measurements has been enlarged to include data on the relation of all pertinent factors of climate and terrain. Such data will be useful in improving the present techniques used to calculate and predict thaw rates and ice melt quantities. The program of meteorological measurements has steadily improved since 1954; in 1957 a fairly comprehensive set of data was obtained. (See section III.) The measurement of soil characteristics is described in section IV.

At the close of the 1957 season not enough data had been accumulated to allow a comprehensive analysis of the entire heat budget at TUTO. This report presents the results of measurements to date and their application to the design of roads on ice and permafrost.

Measured thaw penetration

31. Measurements of the rate and depth of thaw penetration in the undisturbed ground and in road fills have been carried on since 1954. Locations of measurements have been continuously adjusted to provide data on all possible situations. New measuring facilities have been established, old facilities have been abandoned as new structures were constructed, and the program has been revised to meet changing requirements.

Methods of measurement. Two methods have been used to measure the depth of thaw: one was to dig a pit from the surface to the top of frozen soil, and measure the depth with a ru!e; the

other was to insert thermocouples in the soil at intervals of 6 in. or 1 ft and record the temperatures at the level of each thermocouple. The position of the 32 F isotherm is estimated by interpolating between temperatures above and below 32 F read at two thermocouple positions.

These two procedures have some inadequacies. The test pit method is time consuming, individual values are subject to scatter over a range of several inches because it is necessary to dig a new pit at some distance from the previous one every time a thaw depth measurement is desired. However, an advantage to test-pit digging is that test for soil properties such as water content may be run at the same time. The determination of the thaw level from soil temperatures, while fast and convenient, can also be misleading. The accuracy of interpolation depends on the spacing of the thermocouples and the accuracy of the temperature measurements. The method also usually assumes that the freezing temperature of the soil moisture is 32 F, an assumption not necessarily correct.

During the 1956 work season, a new method was used to measure the depth of thaw. Plastic (methacrylate) tubes filled with saturated sand were set in the ground. Two arrangements of tubes were used:

a. Concentric tubes, the outside tube frozen into the ground, the inside tube free to be withdrawn and observed. Lubrication was provided between the tubes - a silicone grease in one set, ethylene glycol in another. It was necessary to provide an air vent for the outside tube (a small-diameter flexible tube leading from the base of the outside tube to the surface) to relieve the pressure of trapped air. The inside tube was filled with a saturated, uniform sand. Readings were taken by withdrawing the inner tube and tilting it so that the thawed sand would fall away from the frozen sand; the distance between the top of the frozen sand and a mark on the tube showing the position of the ground surface was measured and recorded.

b. A single tube frozen in the ground and filled with saturated, uniform sand. The depth to the frozen soil was determined by probing through the thawed sand with a thin, rigid rod.

The concentric tube arrangement was found to give a reasonably accurate measurement of thaw depth when compared with that from a test pit. The saturated sand apparently thaws at about the same rate as the surrounding undisturbed soil, and therefore the device gives a reasonably accurate measure of the general depth of thaw in the ground. However, there were two difficulties in this method. Tilting the tube and loosening the thawed sand, to determine the depth to frozen sand, disturbed the original density, and it was necessary to carefully repack the sand in the tube to its original density every time a reading was taken. When air temperatures dropped below freezing, the top layer of sand froze and it was nearly impossible to determine the thaw depth. Because of these difficulties the device was considered unsatisfactory, but further investigation to develop a device along the same principles is warranted.

It was determined that the single-tube arrangement was impractical. The depth of thaw in the sand was difficult to determine with the probe. Furthermore when freezing air temperatures occurred and the top layer of sand froze, the probe could not be inserted.

Measured depth of thaw in the undisturbed ground. The rate and depth of thaw were measured at several locations in the undisturbed ground by digging pits at regular intervals. Results of some of these measurements are presented in Figures 43 and 44 and Table X. Records for 1956 and 1957 are shown in Figures 43 and 44, respectively. The accumulation of degree-days of thaw for each year is shown with the respective year's record of thaw depth.

It is apparent that the maximum depth of thaw in any one area does not vary appreciably with the air thawing index. In spite of the air thawing index in 1957 being 60% higher than that in 1956, the depth of thaw at all locations varied only slightly from year to year. When a change in the thermal

Table X. Measured Thaw Penetrations

Test Pit No.	Year	Depth of Thaw ft	Air Thawing Index Degree-days F	Remarks
1	1954	2.7	508	Undisturbed surface, silty sand, pronounced patterns
	1955	2.8	397	
2	1954	2.8	508	Undisturbed surface, silty sand, pronounced patterns
3	1954	2.9	508	Undisturbed surface, silty sand, pronounced patterns
4	1954	3.5	508	Undisturbed surface, clayey sand, no pronounced pattern on surface
	1955	3.3	397	
	1956	3.6	380	
	1957	3.7	606	
6	1954	2.8	508	Undisturbed surface, silty sand, pronounced patterns
	1955	2.9	397	
	1956	3.2	380	
	1957	3.4	606	
7	1955	3.25	397	Undisturbed surface, silty sand, pronounced patterns
	1956	3.2	380	
	1957	3.4	606	
8	1956	3.6	380	Undisturbed surface, silty sand, pronounced patterns
	1957	3.7	606	
1A	1955	4.25	397	Gravel road fill (2-1/2 ft) on permafrost
	1956	4.6	380	
	1957	4.75	606	
1C	1955	4.4	397	Gravel road fill (4-1/2 ft) on permafrost
	1956	4.7	380	
	1957	4.8	606	
3A	1955	3.8	—	Gravel road fill (5-1/2 ft) on ice
	1956	4.5	350	
	1957	5.0	580	
5B	1956	2.8	150	Gravel road fill (3 ft) on ice
	1957	3.0	350	

regime occurs, causing degradation of permafrost, the rate of thaw penetration in the active zone, which has little to no segregated ice, is much faster than it is in the permafrost, which has a high ice content. In a slightly cool year, such as 1956, thaw penetrates to the top of permafrost where a change to a fine soil and high ice content occurs. In an abnormally warm year, such as 1957, a degradation of the permafrost of a few inches may occur. Thaw depth was 2-1/2 in. deeper in 1957 than in 1956 in TP6, 1 in. deeper in TP4, and 2-1/2 in. deeper in TP7. However, it should be noted that 226 degree-days of thaw were required to accomplish the added depth. Table X lists the thaw depth for the various locations for all years of record.

Because of heating of the surface by the sun, the permafrost thawed to a considerable depth (10 to 12 in.) before the start of accumulation of degree-days for the air thawing index. Because of the radiation effect, calculations on the basis of the air thawing index alone are prone to give a predicted depth of thaw that is too shallow. For this reason, the most commonly used formula (modified

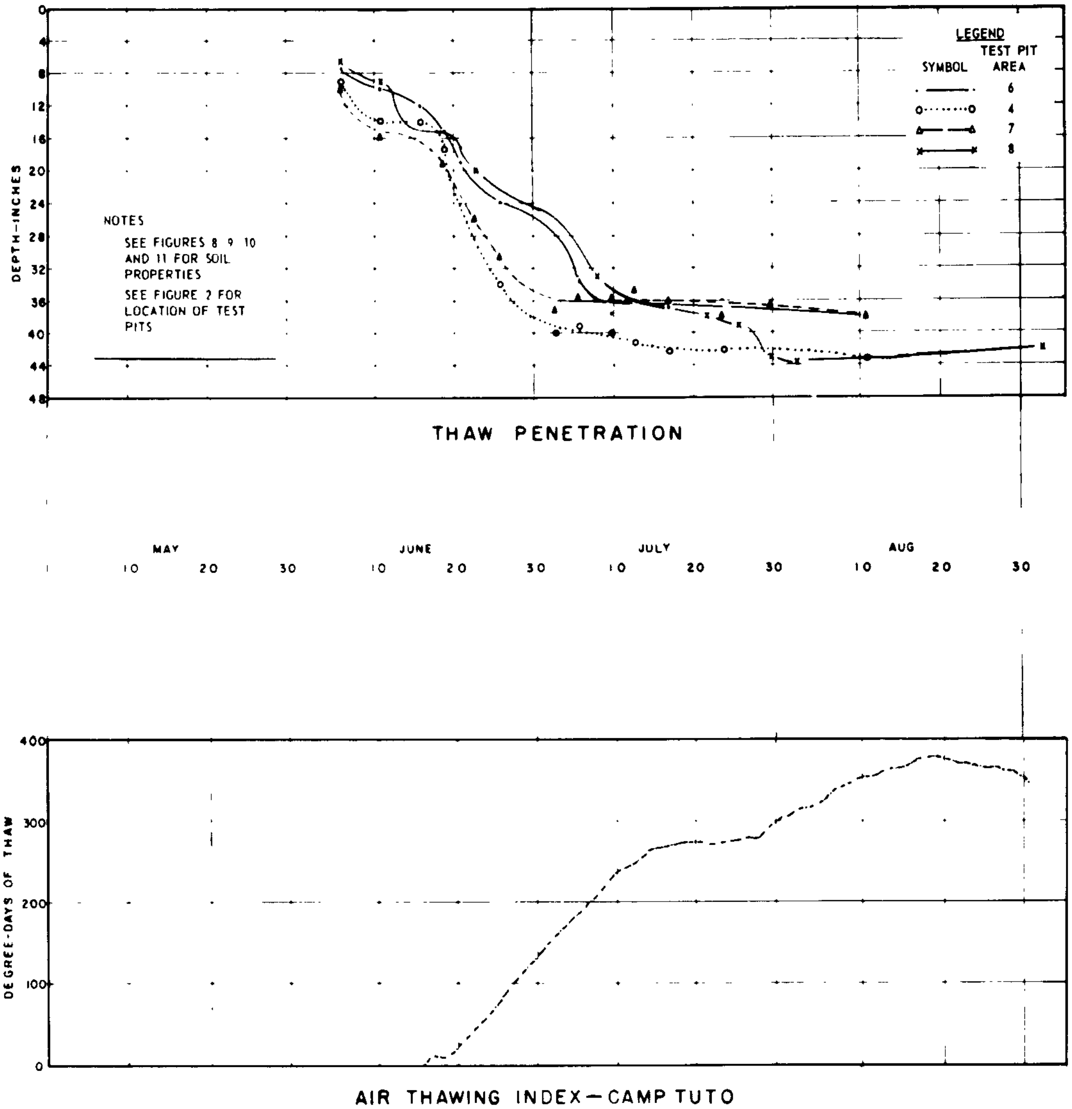


Figure 43. Thaw penetration, undisturbed ground (measured by test pit method), 1956.

Berggren formula) for such calculations employs a factor to represent the ratio between the air thawing index and the surface thawing index. In an area such as TUTO, the solar radiant heat is an especially important factor and the surface temperature is (in the thaw season) appreciably higher than the air temperature. Therefore, the coefficient for TUTO must be appreciably greater than 1.0. The surface thawing index is greater than the air thawing index and, moreover, will cover a different length of time.

As shown in the plots of thaw penetration, Figures 43 and 44, the rates of penetration in the active zone are variable, the trends apparently having some similarity to the variations in climatic conditions as evidenced by the air thawing indexes plotted in the same illustration.

When degradation of permafrost occurs, the rate and extent of thawing are influenced primarily by the ice content and its high volumetric latent heat of fusion.

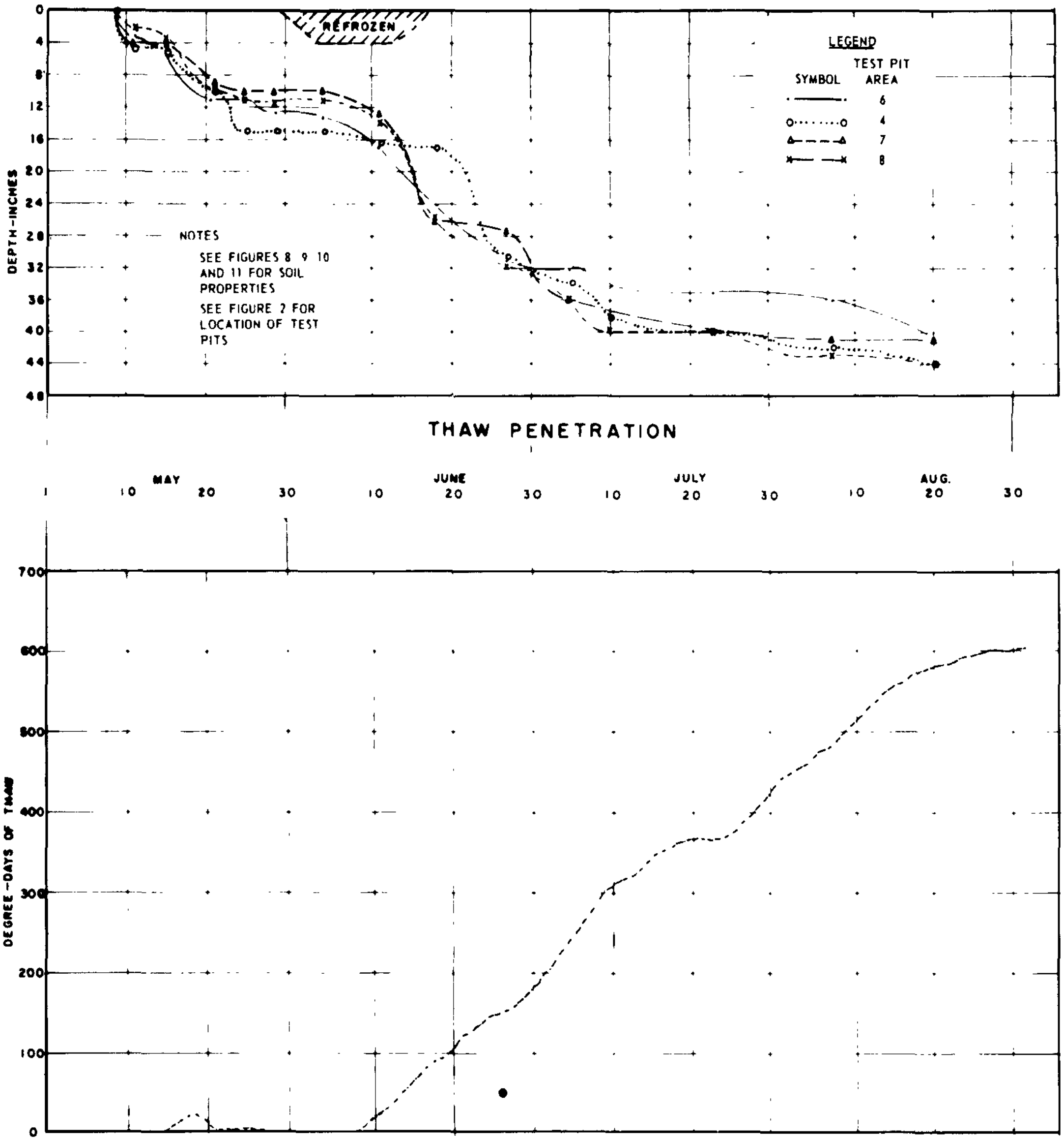
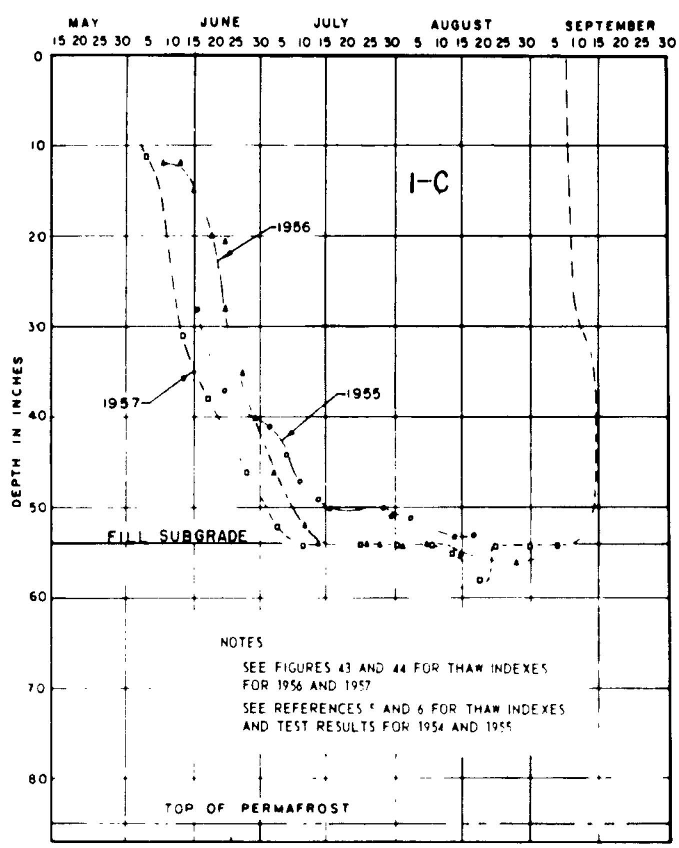


Figure 44. Thaw penetration, undisturbed ground (measured by test pit method), 1957.

Measured depth of thaw in road fills on ground. It was impractical to dig pits in the road fills to determine the depth of thaw; accordingly, the rate of thaw penetration was measured by temperature observations. Thermocouple assemblies were placed in the center of the road fills, and were equipped with leads so that measurements could be made from the side of the road. Readings were taken at least once a week, usually twice a week. Figure 45 shows the thaw penetration in a 4-1/2-ft-thick road fill test section at TUTO. The fill was placed on the undisturbed soil surface; the material for the fill was obtained from adjacent soil areas. Thus, the fill was constructed with the same soil as the underlying active zone. However, compaction and drainage in the fill had increased the dry density and decreased the moisture content by significant amounts. The result was an increase in rate and depth of thaw penetration over that in the natural ground. It may be observed that



DRY DENSITY PCF	MOISTURE CONTENT %	CONDITION WHEN TESTED	SOIL CLASS. SYMBOL
123	6.2	THAWED	SM
130	3.5	THAWED	SM
132	5.2	THAWED	SM
134	5.1	THAWED	SM
133	5.0	THAWED	SM
127	10.4	THAWED	SM
116	13.7	THAWED	SM
127	9.4	FROZEN	SM
92	31.6	FROZEN	ML

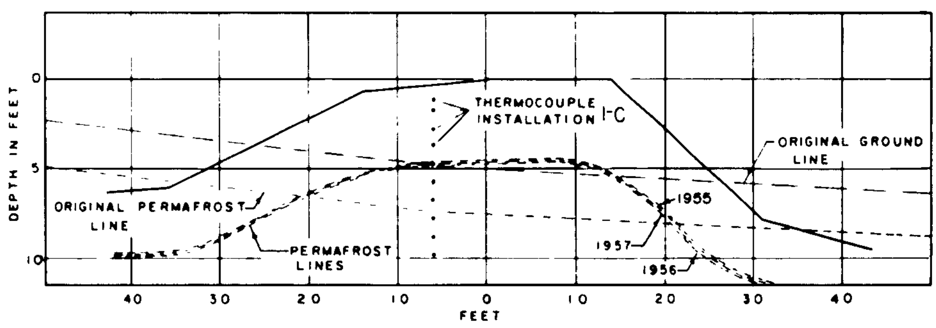


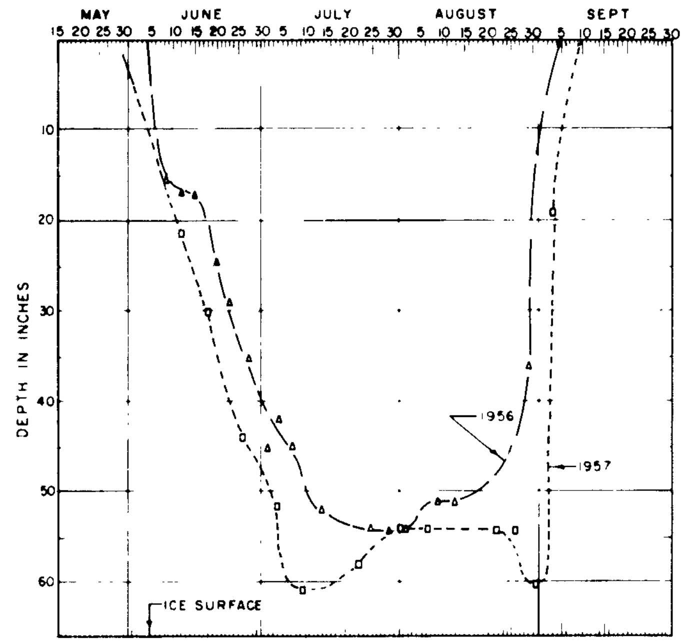
Figure 45. Thaw penetration, 4-1/2-ft gravelly sand fill, Test Lane 1, Station 5 +08.3 (as measured by thermocouples).

thaw penetration slowed or halted under the cooler weather conditions of the last half of July and also as the thaw reached the top of original ground where lower density and higher water content existed.

It can be concluded from Figure 45 that approximately 5 ft of fill with a dry density of 130 lb per cu ft and a water content of 5% would be required to entirely prevent degeneration of

the permafrost and slumping of the fill. However, if a pavement were added to the natural gravel surface it would radically alter the thaw penetration.

Measured depth of thaw in road fills on ice. **Figure 46 shows the thaw penetration at two locations in the Ramp Road fill on the ice for 1956 and 1957. Thaw depths were obtained from temperature readings from thermocouple assemblies embedded in the fill. Depths of thaw and air thawing indexes for the two locations (3A and 5B) for the two years are listed in Table X.**

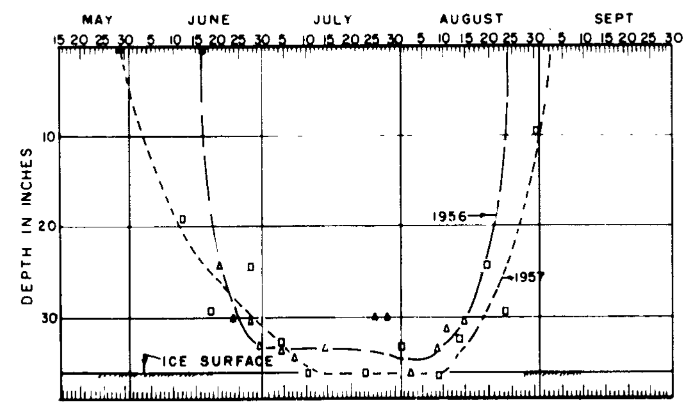


DRY DENSITY pcf	MOISTURE CONTENT %
133	5.0
135	5.0

3A

STA 10+50

NOTES
SEE FIGURE 47 FOR APPROX CROSS SECTION THROUGH 3A
SEE FIGURE 48 FOR CROSS SECTION THROUGH 5B



DRY DENSITY pcf	MOISTURE CONTENT %
133	5.0
135	5.0

5B

STA 77+20

Figure 46. Thaw penetration, gravel fill on ice (as measured by thermocouples).

Location 3A is in Test Lane 3, built in 1954 (Fig. 47). It has approximately 5-1/2 ft of fill consisting of 1 ft of surfacing material having a dry density averaging 133 lb per cu ft and a moisture content of 5%, and the remainder of a coarse material estimated to have a dry density of 135 lb per cu ft and moisture content of 5%. The location at Station 10+50 on the Ramp Road on the ice cap is, of course, colder than a location on the ground. The air thawing indexes for this location were interpolated from the measurements at Met. Stations 1 and 2 (Fig. 5) and are listed in Table X. It is apparent from Table X that, although the air thawing index is slightly lower at location 3A than at 1C on the ground, the thaw penetration at 3A is equal to or greater than that at 1C. The reason may be seen in the depths of fill. At location 1C, there is 4-1/2 ft of fill over a subgrade having a moisture content of 10 to 14% (see Fig. 45). Thaw penetrates to the subgrade and then is slowed or halted. At location 3A, there is 5-1/2 ft of fill which the thaw does not entirely penetrate. As stated before, 5 ft of fill of the type described is required at this location to completely protect the subgrade against melting under conditions of the warmest summer of record.

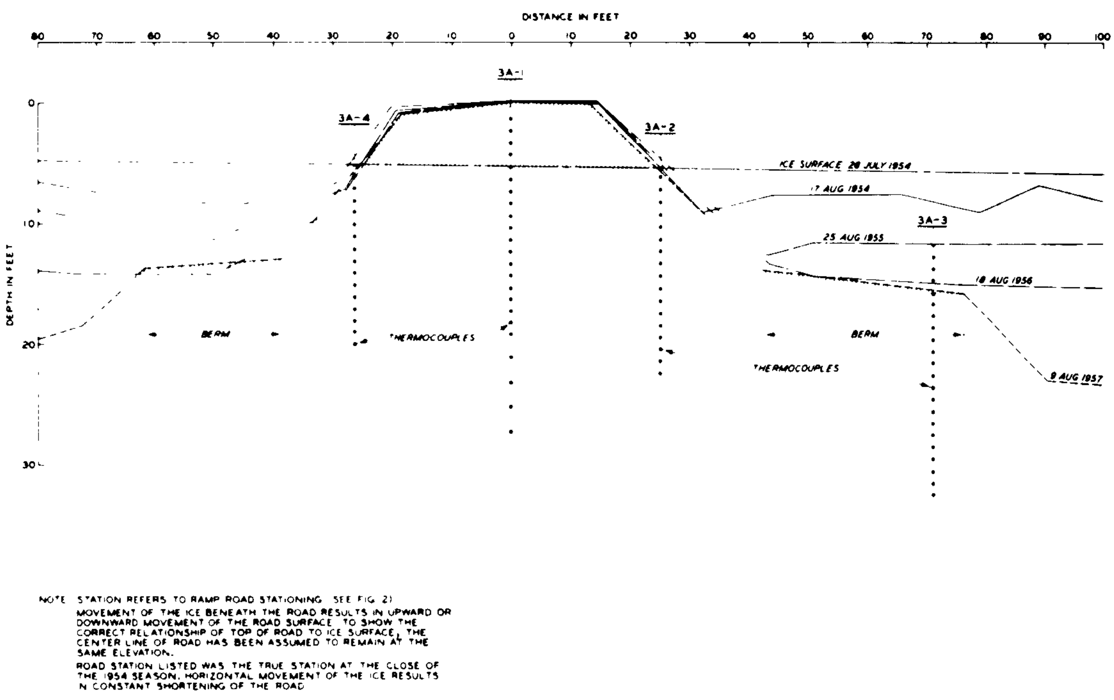
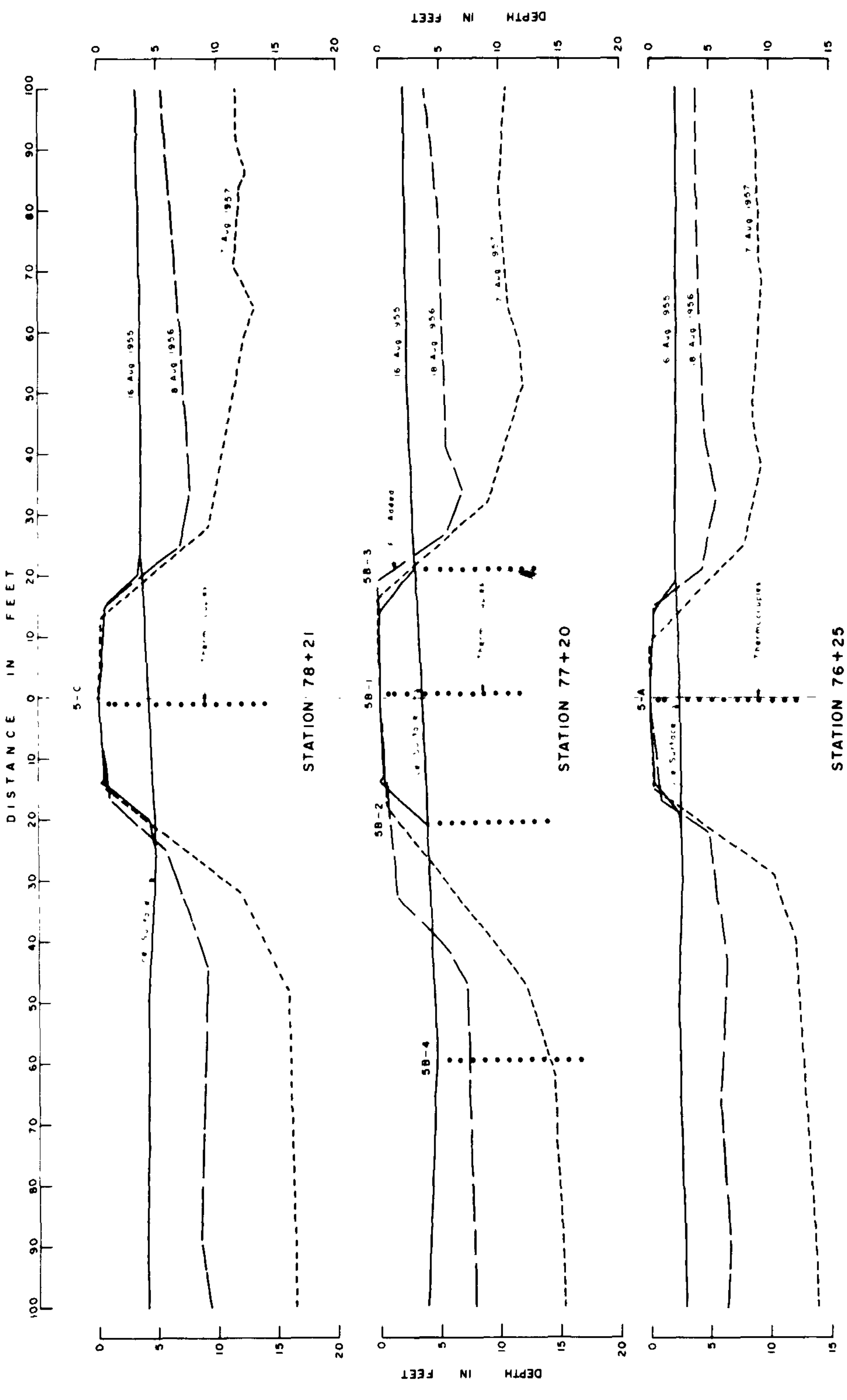


Figure 47. Cross section through Test Lane 3.

At location 5B, there is 3 ft of fill on the ice consisting of 0.5 ft of surfacing material and 2-1/2 ft of coarse material (Fig. 48). This location, at Station 77+20 and elevation 2030 ft, is considerably colder than one on the ground, and the air thawing index, as interpolated between measurements at Met. Stations 2 and 3, is less than half that on the ground at TUTO (Met. Sta 1). (See Fig. 5.) It will be noted that thaw penetrated slightly less than 3 ft in 1956, a cooler than normal year; and in 1957, an unusually warm year, the thaw penetrated the entire 3 ft with considerable heat to spare, which warmed and melted the ice subgrade. Thus, complete protection from subgrade melt was *not* afforded by 3 ft of fill at this location for the warmest summer experienced. However, the thickness of ice melted beneath the fill was apparently small and was tolerated by the flexible gravel fill. The gravel fill could continue to tolerate this amount of subgrade ice melt if it occurred only during an occasional warm year.



NOTES

(1) Stations refer to Ramp Road stationing (See Fig. 2)
(2) Movement of the ice beneath the road results in upward or downward movement of the road. To show correct relation of top of road to top of ice surface, the center line of road has been assumed to remain at the same elevation
(3) Road stations listed were true stations at the close of 1957 thaw season. Horizontal movement of the ice results in constant shortening of the road.

Figure 48. Cross section through Test Lane 5.

Prediction of thaw penetration

32. During the past several years sufficient measurements of thaw penetration, soil properties, and meteorological data have been collected in the TUTO area to test one of the formulas used to compute thaw penetration. The following paragraphs present a discussion and application of an accepted penetration prediction formula. Symbols and notations used throughout this section are given in Table XI.

Table XI. Notations

Symbol	Name	Unit
C	Volumetric heat $= \gamma_d\,(0.17 + 0.0075\,w)$	Btu/(cu ft) (°F)
d	Thickness of layer	Feet
F	Degree-days F required to thaw a given layer of soil	Degree-days F
F_a	Air thawing index	Degree-days F
F_s	Surface thawing index $= nF_a$	Degree-days F
K	Thermal conductivity	Btu/(hr) (ft) (°F)
L	Latent heat $= 1.44\,\gamma_d w$	Btu/cu ft
n	$\dfrac{\text{Surface thawing index}}{\text{Air thawing index}}$	Dimensionless
R	Thermal resistance of a layer of soil	(hr) (°F)/Btu
t	Time, duration of thaw season	Days
V_o	Degrees F by which mean annual temperature varies from freezing point of soil moisture. At TUTO mean annual temperature is taken as + 10 F, thus $V_o = 32 - 10 = 22$ F	Degrees F
V_s	Degrees F by which effective surface temperature varies from freezing point of soil moisture $= \dfrac{nF_a}{t}$	Degrees F
w	Moisture content	Percent
x	Depth of thaw	Feet
α	Thermal ratio $= \dfrac{V_o}{V_s}$	Dimensionless
γ_d	Dry density	lb/cu ft
λ	Coefficient which is a function of two dimensionless parameters α and μ	Dimensionless
μ	Fusion parameter $= \dfrac{C}{L}V_s$	Dimensionless

Procedure. An accepted formula for computing thaw penetration is the "modified Berggren formula":

$$x = \lambda\sqrt{\frac{48\,KnF_a}{L}}\,. \tag{1}$$

This formula may be used to determine thaw penetration for homogeneous soils; however, for soils that contain layered systems, the formula must be adjusted to account for the variation in physical characteristics of the various layers under consideration. For layered systems, the number of

degree-days required to thaw each layer from the surface downward is determined and accumulated until the total approximately equals the available degree-days (F_s). For layered systems, equation 1 becomes:

$$d = \lambda \sqrt{\frac{48\,KnF_a}{L}}\,. \tag{1}$$

Weighted values of C and L are determined for each layer from which α and μ are computed, and λ is obtained from a nomograph that relates α, μ, and λ (see reference 2). A thermal resistance ($R = \frac{d}{K}$) is also computed for each layer. For the individual layers equation 1 becomes:

$$F_1 = \frac{L_1 d_1}{24} \cdot \frac{R}{2} \cdot \frac{1}{\lambda^2} \qquad \text{1st layer}$$

$$F_2 = \frac{L_2 d_2}{24} \left(R_1 + \frac{R_2}{2}\right) \frac{1}{\lambda^2} \qquad \text{2nd layer}$$

$$F_n = \frac{L_n d_n}{24} \left(\Sigma R + \frac{R_n}{2}\right) \frac{1}{\lambda^2} \qquad n\text{th layer}\,. \tag{2}$$

The assumptions made in deriving the modified Berggren formula limit its application to some extent. A step change in temperature at the surface is assumed, and other modes of fluctuation of ground-surface temperature may not be taken into account. Accordingly, the formula is applicable only for maximum depths or when the entire thaw season is considered. The equation is one-dimensional and predicts thaw penetration in depth only.

Surface thawing index to air thawing index ratio (n). It is usually possible to obtain at least approximate values for all terms used in equation 1 except n. A value of this ratio is usually necessary because the surface thawing index F_s is seldom available, and a modified air thawing index must be used to represent the surface thawing index. Reliable values for n are obtained by substituting measured values for thaw depth, soil, and meteorological data in equation 1 and solving for n. This procedure obviously has some drawbacks, especially in that the accuracy of the resulting value for n depends upon the accuracy of the measured data as well as on the ability of the formula to represent the true situation. Unfortunately, any or all of these discrepancies may be present. The resulting error then falls into the computed value of n. However, when reasonable agreement is obtained for the same year and for several locations, the error must be at least consistent, and it is possible to attempt some correlation with other factors with a fair degree of confidence.

In 1957 surface temperatures were measured during most of the thaw season (the remainder were estimated) permitting the computation of surface thawing index directly. Computing n by comparing the "measured" surface thawing index with the air thawing index gave a value of 1.46. Values of n for several selected sites were also computed by substitution in the Berggren formula, and they are shown along with average wind velocity and cloud cover in Table XII. For 1957 the computed values for n were found to range between 1.4 and 1.5.

It will be noted in Table XII that n varies widely from year to year but only slightly from place to place in the same year for those surfaces (undisturbed ground and surface of road fills) for which data were available. Apparently the difference in n in the same year is caused by surface differences in texture and color that are too small to be detected by this method. Radiational heat plays a major part in the difference between air temperature and surface temperature, and a difference in n from year to year may be expected because of differences in factors such as wind

Table XII. Relation of Computed Surface Transfer Coefficient n to Air Thawing Index, Wind Velocity, and Cloud Cover

Test Pit	Year	Air Thawing Index	Surface Correction Factor n	Surface Thawing Index	Avg Wind Velocity for Season mph	Avg Cloud Cover Tenths	Remarks
7	1955	397	2.0	794	10.2	5.0	Undisturbed ground
	1956	380	2.1	798	11.3	5.3	
	1957	606	1.4	848	15.7	6.2	
8	1956	380	2.1	798	11.3	5.3	Undisturbed ground
	1957	606	1.5	909	15.7	6.2	
1C	1955	397	2.1	834	10.2	5.0	Road fill on ground
	1956	380	2.1	798	11.3	5.3	
	1957	606	1.4	848	15.7	6.2	
3A	1956	350	2.1	735	11.3	5.3	Road fill on ice
	1957	580	1.5	870	15.7	6.2	
5B	1956	150	2.2	660	11.3	5.3	Road fill on ice

velocity, cloud cover, and other climatic variations that affect the radiational heat.

Table XII shows that n varies inversely with the average wind velocity and cloud cover.

It is standard practice to use the highest air thawing index obtained in a 10-year period (if available) as a design index, but this must be modified to design surface thawing index. It is obvious that using the greatest n, together with the highest air thawing index, would result in an unrealistic surface thawing index. The depth of thaw would be greatly overpredicted. Table XII indicates that the year (1957) with the highest air thawing index is also the year with the highest surface thawing index, but n for this year is considerably less than for the other years. As yet final conclusions are not possible regarding the proper n to be used to predict thaw penetration. Some correlation of n with usually available weather data, such as wind velocity, would be helpful. Again, the data are too meager to effect such a correlation. Several more years of data are required, or possibly a different approach to the determination of n should be considered.

In the absence of a definite value for the n ratio, and with only 4 years record of the air thawing index, the best value to use as a design value or prediction value would be the highest computed surface thawing index so far recorded, or about 900 degree-days (Table XII). Thaw penetration values may then be computed if soil density, moisture content, and type are known, together with mean annual surface temperature and length of thaw season.

Example of depth of thaw prediction in a homogeneous soil embankment. The following example deals with the determination of the thickness of pad or base course required to prevent thaw of the frozen subgrade in the TUTO area. The climatic data obtained in 1957 are used in the example. The soil used to construct such an embankment might be similar to that of the road fill described in Figure 45, or a silty sand having a dry density of about 132 lb per cu ft and a moisture content of about 5%. The mean annual surface temperature, as shown by the subsurface temperature measurements (Fig. 17), is taken as +10 F since this temperature appears to remain stable regardless of season. Length of thaw season is taken as 80 days (Table V).

Using equation 1 the depth of thaw can be calculated as follows:

$$F_s = 900 \text{ degree-days F}$$

$$^*K = \frac{1.55 \text{ (unfrozen)} + 1.45 \text{ (frozen)}}{2} = 1.50/\text{Btu}/(\text{hr})\ (^\circ\text{F})$$

$$L = 1.44 \times 132 \times 5.0 = 950 \text{ Btu/cu ft}^2$$

$$\alpha = \frac{V_o}{V_s} = \frac{32 - 10}{\frac{900}{80}} = \frac{22}{11.25} = 1.95$$

$$\mu = \frac{C}{L}\ V_s = \frac{132\ [0.17 + (0.0075 \times 5.0)]}{950} \times 11.25 = 0.324$$

$$\lambda = \text{function of } \alpha \text{ and } \mu = 0.568 \text{ (see reference 2)} .$$

Substituting the above-listed values in equation 1:

$$x = 0.568 \sqrt{\frac{48 \times 1.50 \times 900}{950}}$$

$$x = 4.7 \text{ ft} .$$

Similar computation for 1956 gave a computed depth of thaw of 4.6 ft. A comparison of actual versus computed depth of thaw (Fig. 45) for 1956 and 1957 shows close agreement between actual and computed depths of thaw. It can be seen that 5 ft of silty, gravelly sand fill is required for complete protection of subgrade thaw in the TUTO area.

Example of depth of thaw prediction in road fills on glacier ice. Another important problem is the determination of the thickness of soil fill required on the ice ramp to prevent the underlying ice from melting. It is necessary to prevent such melt or to minimize it because the meltwater tends to saturate the road fill and the irregular melting of the ice results in a rough road surface. It is assumed ice melt of the order of 0.1 to 0.2 ft per year can be tolerated, since the road surface can be corrected for this amount of melt with a minimum of maintenance. However, the actual performance of a road fill on ice should be observed for several more years before this assumption can be validated.

The amount of ice melt beneath a given gravel embankment can be estimated by using the procedure already described for a multilayered soil system. Assume a road fill as described for location 5B in Test Lane 5 (shown in Fig. 46), that is, a 6-in. surface layer of soil with a dry density of 133 lb per cu ft and a moisture content of 5% overlying a 2.5-ft depth of soil with a dry density of 135 lb per cu ft and moisture content of 5%. The air thawing index of 427 degree-days, which was measured in 1957 at Met. Station 2 (Table V), is also used in the example. The air thawing index (427 degree-days) can be converted to a surface thawing index (640 degree-days) by multiplying by an n factor of 1.5. Mean surface annual temperature is again taken as +10 F and length of thaw season as 80 days. The problem is conveniently set up in tabular form, as follows:

* See reference 4.

Thermal Resistivity of Layers

d	C	K	L	ΣLd	$\frac{\Sigma Ld}{\Sigma d}$	ΣCd	$\frac{\Sigma Cd}{\Sigma d}$	μ	λ*	R
0.5	27.6	1.54**	958	479	958	13.8	27.6	0.230	0.292	0.32
2.5	28.0	1.62**	972	2909	970	83.8	27.9	0.230	0.292	1.54
0.1*	28.0	1.30†	8000	3709	1196	86.6	27.9	0.187	0.325	0.08

* See reference 4.
** Ice layer.
† See reference 10.

Degree-days Required to Thaw Each Layer

d	R_n	ΣR	$\Sigma R + \frac{R_n}{2}$	Degree-days	Accumulative Degree-days
0.5	0.32	0	0.16	10.9	10.9
2.5	1.54	0.32	1.09	377.5	388.4
0.1	0.08	1.86	1.90	195.0	585.7

In the tabulation for the degree-days required (above) $\Sigma R + \frac{R_n}{2}$ for the first layer includes only $\frac{R_n}{2}$ or 0.16 since there is no layer above it. In the second layer $\Sigma R + \frac{R_n}{2}$ includes R_n for the first layer plus $\frac{R_n}{2}$ for the second layer or 0.32 plus $\frac{1.54}{2}$ which equals 1.09. For the third layer $\Sigma R + \frac{R_n}{2}$ is obtained by totaling R_n for the first and second layers plus $\frac{R_n}{2}$ for the third layer or $(0.32 + 1.54) + \frac{0.08}{2}$ which equals 1.90. The computations in the above tabulations show that about 388 degree-days of thaw are required to thaw the 3-ft road fill, leaving 252 degree-days (640 − 388) for melt of the underlying ice. However, 0.1 ft of ice will require 195 degree-days to melt, or a total of 0.13 ft of ice will melt under 3 ft of gravel fill at a location 1 mile from the edge of the ice ramp. To reduce the ice melt to zero a total thickness of fill of approximately 3.8 ft is required in the road section 1 mile from the edge of the ice ramp. At Met. Station 3, 3 miles from the edge of the ice, the air thawing index in 1957 was 294 degree-days (Table V). When the n factor of 1.5 is applied, the surface thawing index would be 441 degree-days. A similar computation to that just undertaken shows that 3 ft of fill will give *complete* protection from ice melt at this location.

It will be noted that the computed results are supported by the measured results (Fig. 46) insofar as the measurements were adequate. No actual amounts of ice melt beneath the fill have yet been measured with accuracy; the requirement is noted for the future.

Summary

33. Two new methods for measuring thaw depth were investigated in the hope that they might offer some advantages over test pits and use of thermocouples. The first method, a device consisting of two concentric tubes, the inner tube filled with saturated sand, was found to be inconvenient because of the necessity of repacking the sand in the tube after dislodging the sand to find the thaw line. The thaw line was impossible to determine when a brief cold period froze the top few inches. In

the second method, a single plastic tube was filled with saturated sand and embedded in the ground. Thaw depth was determined by probing in the sand with a thin, rigid rod. This method was not feasible.

Measurements of the depth of thaw in the undisturbed ground in the TUTO area, obtained by digging test pits at approximately weekly intervals throughout each thaw season, showed average penetrations of 2.9 ft in 1954, 3.1 ft in 1955, 3.4 ft in 1956, and 3.6 ft in 1957.

The following thaw penetrations were measured in road fills by means of thermocouples:

1957: Thaw in road fills (constructed by bulldozing into stockpiles the adjacent active zone soils) penetrated 4.8 ft below the surface of a 4.5-ft fill and 4.75 ft below the surface of a 2.5-ft fill. (The summer of 1957 was the warmest summer on record.)

Depth of thaw in a 5.5-ft-thick gravel road fill on the ice, 1000 ft out on the ice ramp, was 4.8 ft.

1956: Depth of thaw in a 3-ft-thick gravel road fill on the ice, 7700 ft out on the ice ramp, was 2.8 ft. In 1957, the entire 3 ft of fill thawed prior to the end of the thaw season; some melt of the ice beneath the fill must have occurred but the amount was not measured.

The data obtained from measurements of soil properties, depths of thaw, and meteorological properties were used to establish the factor n, defined as the ratio of air thawing index to surface thawing index. The factor is required when making predictions of thaw depth based on the modified Berggren formula or adaptations of that formula.

Computations of the n ratio at selected locations showed that n was 2.1 to 2.2 in 1956 for the undisturbed ground and for the gravel roads. In 1957, the n factor was 1.4 to 1.5 for the same surfaces.

Observations indicated that variation of surface thawing index at a given point is much less than the variation of air thawing index.

The modified Berggren formula was used to determine the depth of thaw in a homogeneous road fill having characteristics similar to the actual test section where measurements were taken. For the calculation, the surface thawing index was taken as 900 degree-days for 1957, the warmest year on record. The mean annual temperature was taken as +10 F and the length of thaw season as 80 days. A depth of thaw of 4.7 ft was computed as compared to 4.8 ft measured.

Computations by an adaptation of the Berggren formula for multilayered soils indicated that the amount of ice that would have melted in 1957 beneath a 3-ft gravel fill was about 0.25 ft at a point 1000 ft from the edge of ice, about 0.15 ft at 7700 ft from the edge of ice, and none at 3 miles from the edge of ice.

VII. ROAD CONSTRUCTION

34. Road construction in 1956 and 1957 was primarily a continuation of the road construction commenced in 1955 to make existing roads more useful from an operational standpoint and to construct new ones to satisfy investigational requirements. In 1955, the Ramp Road construction had been completed as far as Station 97 + 00, which was well within the ablation area. In 1956, the road was extended to Station 159 + 00 which placed the end of the road in the marginal zone between the ablation and accumulation zones. Likewise in 1955, 800 ft of Transverse Road had been constructed, leading from the Ramp Road at about Station 27 + 00 toward the base of the moraine formation to the north.

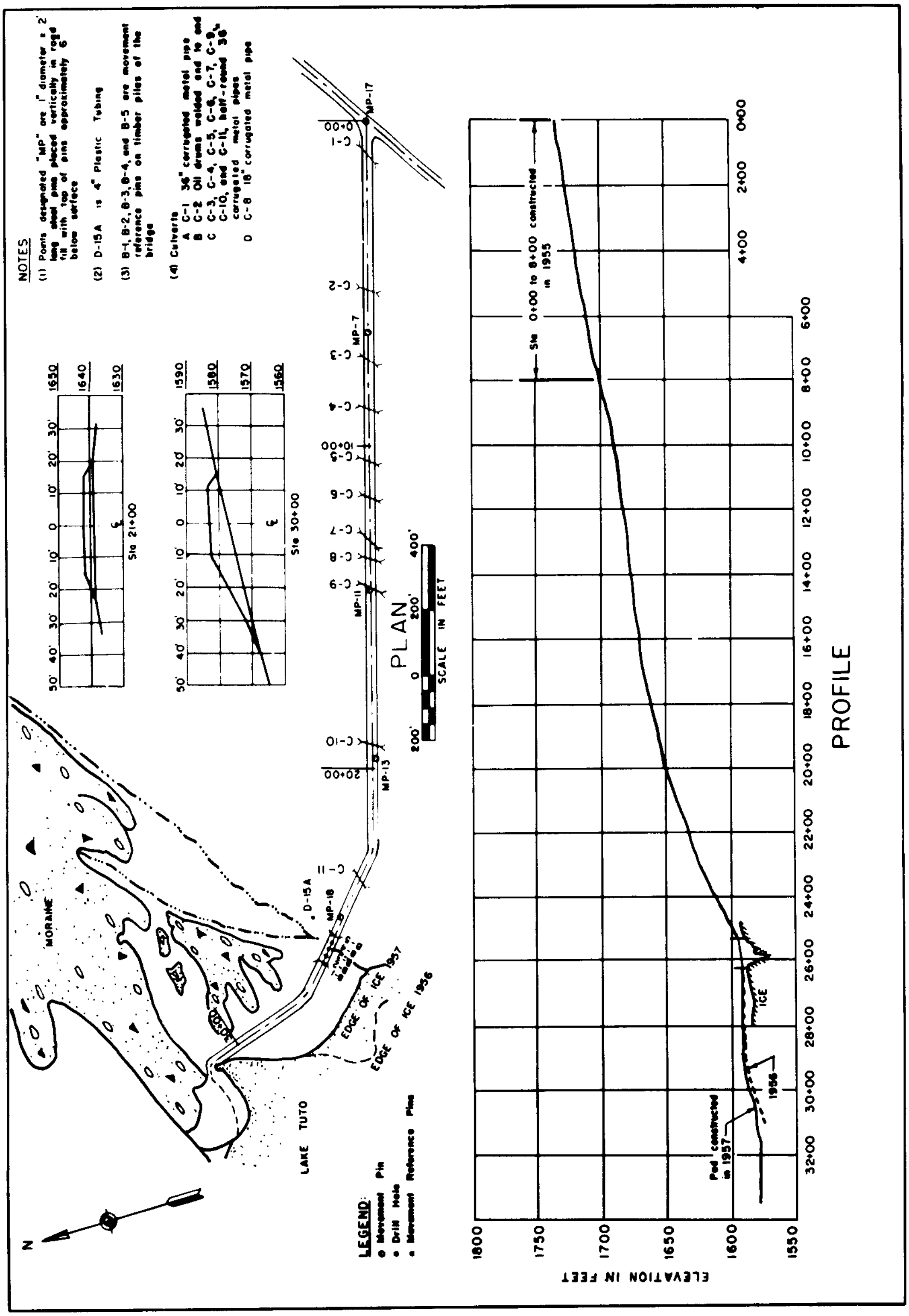


Figure 49. Transverse Road, 1957.

That section of road served only to provide information on the feasibility of constructing a road at right angles to the direction of meltwater streams. In 1956, the road was extended across the ramp, skirting the base of the moraine, and thus providing access to the experimental ice tunnel under construction in the ice cliff northeast of Lake TUTO.

Program

35. In 1956, road construction did not start until 3 July. The delay was due to the extraordinarily deep snow cover which made it necessary to plow snow from the access roads, dig out the equipment from deep snowdrifts, and wait for the snow cover to melt from the borrow areas. The snow cover on the ramp softened and melted first in the area near the Transverse Road. Therefore, the extension of this road was constructed first and the extension of the Ramp Road second. Final construction in the 1956 season was the berms for the first 2500 ft of Ramp Road.

The thaw season commenced early in 1957. The only section of new road constructed was the continuation of the Transverse Road to include a large pad in front of the entrance to the ice tunnel. During the remainder of the 1957 season, construction was confined to experimental berms and a test section of road using thin fills of crushed rock.

Transverse Road

36. The Transverse Road was constructed as shown in Figure 49. The first 800 ft constructed in 1955 was only 24 ft wide. The first operation in 1956 was to widen this section to 30 ft to allow two-way traffic of large trucks. Construction of the new section of road was carried on as in 1955 by end-dumping from the 10-cu-yd trucks and spreading and compacting with a D8 bulldozer. Since as much as 3 ft of snow still lay on the ice surface, it was necessary to plow the snow ahead of the road construction. The snow was wet and heavy, but a skilled operator with a D8 bulldozer was able to handle it without serious difficulty. (An attempt to compact the snow rather than plow it for one experimental section is described later.)

Road design. A minimum depth of fill of 3 ft was required to allow the installation of cross-drainage culverts. This resulted in a minimum depth of 2.5 ft of coarse fill. Gradation of the coarse fill is shown in Figure 21 (borrow pit L). The usual surfacing of fine material (gradation shown in Fig. 22 for borrow pit H) was placed to a depth of at least 0.5 ft. Two typical cross sections of road are shown in Figure 49. Quantities of fill used are shown in Table II.

Keying the road fill to ice slope. For a short distance at Station 30+00, the road crossed a fairly steep slope in the ice surface. To prevent sliding of the road fill, a deeper fill was used to keep the base of the fill frozen to the ice. In addition, the road fill was keyed into the ice by excavating trenches to receive the gravel material. Figure 50 shows the layout of the trenches which were excavated by blasting, as follows. For each trench, holes were drilled in the ice 3 ft deep and approximately 5 ft apart. Each hole was loaded with 1-1/4 lb of dynamite. The resulting trench was 4 to 5 ft wide and 3 to 4 ft deep. As shown in

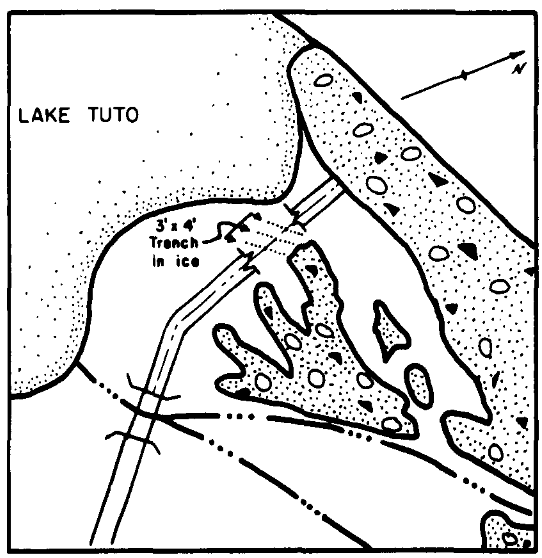


Figure 50. Anchoring of Transverse Road fill on ice slope.

Figure 50, three trenches, each 30 to 40 ft long, were excavated. The procedure was apparently effective as no sliding of the road has been detected.

Placing of road fill on compacted snow. An experimental section of road was constructed in which the gravel road fill was placed on compacted snow rather than on the bare ice surface. The only available equipment for compaction were the D8 bulldozers with standard-width treads, and it was found that their high ground pressure resulted in excessive rutting and displacement of the snow. However, it was possible to compact the snow sufficiently to carry the road fill. The result was satisfactory from the standpoint of bearing capacity, but difficulties resulted from erosion of the snow-ice ridge by flowing meltwater. During the height of the melt season, water would sometimes pond on the uphill side of the road and run through the coarse gravel fill. Where the compacted snow was present, the flow very quickly eroded the snow ice and caused a subsidence in the overlying road surface.

Culverts. Figure 2 shows that the Transverse Road crosses the natural downslope direction of meltwater flow at a considerable angle. Consequently some provision was necessary to carry the flow to the downhill side of the road. In 1955 experiments had been made with four types of culverts: a 36-in.-diameter corrugated metal pipe (culvert C-1); a French-drain type in which a trench was filled with boulders; a pipe made of 55-gal oil drums with the ends cut out and welded end to end (culvert C-2); and a so-called bridge-type culvert where the natural meltwater channel was bridged with a half-round corrugated metal pipe 36 in. in diameter (culvert C-3). At the close of the 1955 thaw season only the bridge-type culvert remained functional; the others had become perched above the flow line because of the differential melting of the ice surface adjacent to and under the road. Accordingly, it was decided to use the bridge-type culvert in the new road construction in 1956. As shown in Figure 49, seven of these culverts (C-4 through C-7 and C-9 through C-11) were placed in the road at places where meltwater channels crossed the road. One other type of culvert (C-8), and 18-in.-diameter, round, corrugated metal pipe, was also used. Generally, an attempt was made to follow the natural alignment of the channels, but if this was not practical the channels were straightened and cleared of ice with axes or chisels.

Performance. The eight culverts placed in 1956 functioned for the remainder of the 1956 thaw season, except for brief periods when they were blocked with snow. An unusual number of snowfalls occurred in the 1956 season, and snow accumulation was perhaps abnormal. In a normal season, the number of blockages due to snow accumulation during the thaw season would be few, if any.

In the unusually warm season of 1957, a different situation was encountered. Ablation of the ice was rapid and meltwater flow quantities were very large (Fig. 51). The

Figure 51. Meltwater flow at toe of Transverse Road. Note high velocity on steep slope approaching the bridge (2 July 1957).

ablation and erosion of ice on the uphill side of the road proceeded much more rapidly than the flowing meltwater could cut a channel in the ice. Consequently, all culverts eventually became perched above the flow line (Fig. 52). Meanwhile, it was noted that the capacity of the culverts was inadequate, even when they were running full (Fig. 53). By 24 June 1957, water was ponding on the uphill side of the road. Of the 11 culverts, all were working except C-1, C-2, C-3, C-4, and C-8 which had become perched above the flow line. On 3 July culverts C-5, C-6, C-9, and C-11 were running full; culverts C-7 and C-10 were submerged, but flow was partially blocked. At this time, ponded water was threatening to overtop the road.

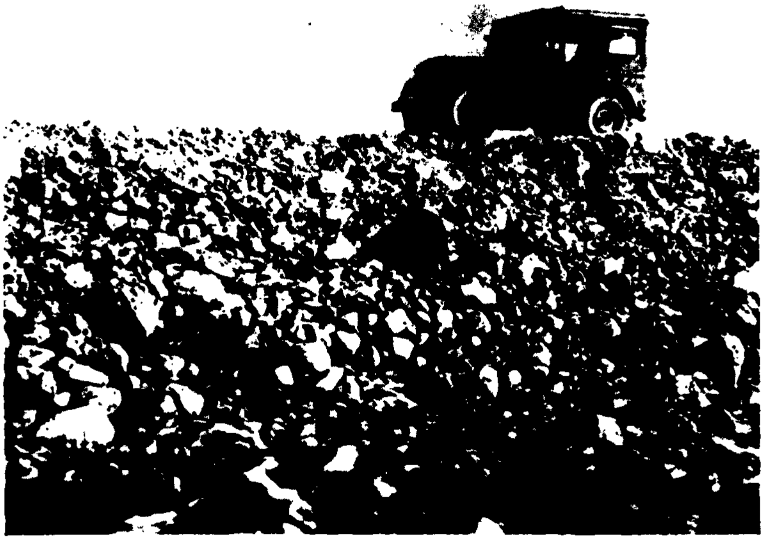


Figure 52. Corrugated metal pipe culvert perched above ice surface. Pipe was originally set slightly below ice surface (29 June 1957).

Figure 53. Meltwater flow at toe of Transverse Road. Note that rapid flow bypasses culvert (5 July 1957).

When flow was rapid, erosion of the ice supporting the corrugated metal arch was rapid. Culverts C-9 and C-6 (Fig. 54) eventually collapsed because of this erosion.

Figure 54. Half-round, corrugated metal pipe culvert. Erosion of the ice by flow of meltwater has resulted in collapse of culvert (29 June 1957).

Analysis of results. It was demonstrated that the half-round, 36-in.-diameter, corrugated metal pipe culvert (bridge type) was inadequate because: (1) it had insufficient capacity to handle peak flow; (2) it was easily blocked with snow, ice, and soil debris; (3) the supporting ice eroded rapidly and the culvert was then likely to collapse; and (4) it tended to become perched above the flow line after one normal thaw season.

Nevertheless, the bridge-type culverts functioned for part of the 1956 thaw season and the first half of the 1957 thaw season. One such culvert, C-4, functioned part of the 1955 season, all of the 1956 season, and part of the 1957 season. It follows that the principle of bridge-type culverts is satisfactory; however, the dimensions should be enlarged.

Work pad at tunnel entrance. Construction of the Transverse Road was completed to about Station 31 + 00 (Fig. 49) in 1956, somewhat short of the actual ice tunnel entrance. In this construction, the road fill was extended across a small gully. Clean boulder fill was used and an 18-in.-diameter corrugated metal pipe was placed in the lowest part of the gully. In 1957, the road was completed to the tunnel work pad which was approximately 200 by 200 ft. Construction of the pad included the leveling of a small hillock located directly in front of the tunnel entrance (Fig. 55). The hillock consisted of solid ice covered with 1 or 2 ft of moraine. The leveling was accomplished by blasting successive layers of ice and clearing it with bulldozers until a suitable elevation in relation to the floor of the tunnel was reached. A gravel fill 1.5 ft deep covered with a surfacing of fine material 0.5 ft thick was placed on the leveled ice surface. The finished pad is shown in Figure 56.

The extension of the Transverse Road to the pad required raising the height of fill across the small gully. The crossing remained stable, although some ponding of water occurred above the fill during brief periods of heavy thaw and ice melt, particularly after the culvert pipe was blocked with boulders and ice.

Road performance. The road performed satisfactorily throughout the observation period (1956-1957). It supported the traffic of trucks weighing up to 20 tons, and occasionally heavier loads when mining machinery was transported to the tunnel area. By the middle of August 1957, ablation of the surrounding ice and erosion by the heavy meltwater flow along the toe of fill had caused considerable slumping of the shoulders. As a result, the road was too narrow for two-way traffic in some places. The surface of the road was rough where the road had settled over the culverts. Repairs were made by resurfacing and replacing fill in the shoulders to bring the road to a minimum width of 30 ft.

Figure 55. Moraine formation (coarse gravel covering ice core) at site of entrance to ice tunnel (Aug 1955).

Figure 56. Work pad constructed at entrance to ice tunnel by cutting the moraine shown in Figure 55 (2 June 1957).

Thereafter, the road remained usable without further maintenance. The necessity for repairs was partially due to the very warm season of 1957. In a more normal season, the damage to the road from excessive melt would be proportionately less and demands for repair reduced. Failure of the culverts to carry the flow resulted in an undesirable quantity of water flowing at the toe of fill. Adequate water-crossings in the road would have prevented much of the damage caused by erosion. Berms on each side of the road would have prevented the slumping of the shoulders caused by the ablating ice surface.

The movement of the ice apparently has little or no effect on the gravel fill of the Transverse

Road. However, the rate of movement is small (see Table VI), ranging between 1 and 2 ft per year in the direction of the edge of ice.

Ramp Road

37. Figures 57 and 58 show the extension of the Ramp Road from Station 97 + 00 (the end of the road in 1955) to Station 159 + 17, the final end of the road. Construction was commenced on 15 July 1956 and completed by 19 August 1956, except for the fine surfacing on the last 500 ft which was placed in 1957. Figure 2 shows that the alignment was a continuation of that used in 1955. The direction was roughly that of the trail used by the sled trains. The last 2000 ft passes a small hill to the north. It will be noted that the slope averages only 3% in this last half mile.

Disposal of snow cover. Snow conditions in 1956 delayed the scheduled start of road construction for 2 weeks. The snow cover was 3 to 4 ft deep over the entire area and about 1 ft deep on the existing road. This condition was aggravated by drifts that were 10 to 15 ft high at some places on the existing road where sleds or caches of POL had been left along the road the previous year. It was necessary first to remove the snow from the road, and then to spread out the high windrows of snow left alongside the road. These large windrows, melting slowly, kept the road surface constantly saturated and subject to damage by the truck traffic.

When road construction was finally commenced there was still approximately 2 ft of snow on the adjacent ice. Until the snow had melted to less than 1 ft, it was plowed from the ice surface

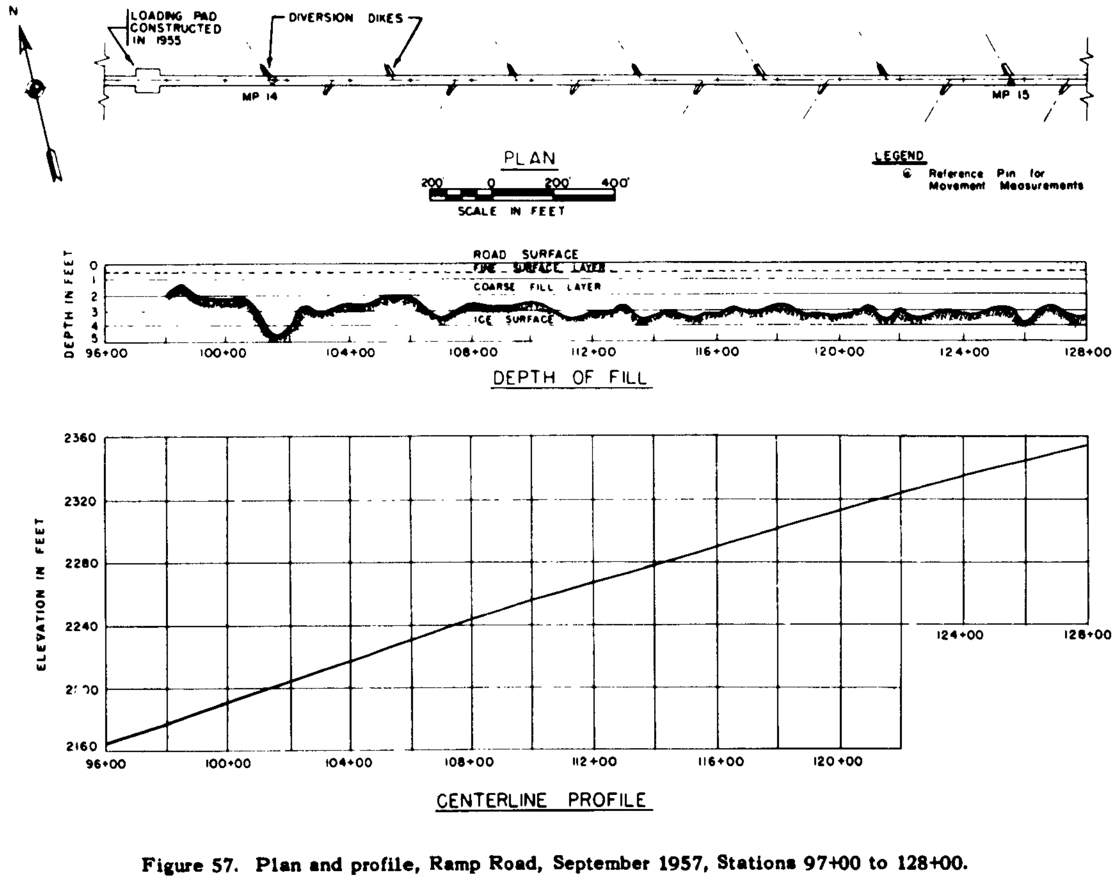


Figure 57. Plan and profile, Ramp Road, September 1957, Stations 97+00 to 128+00.

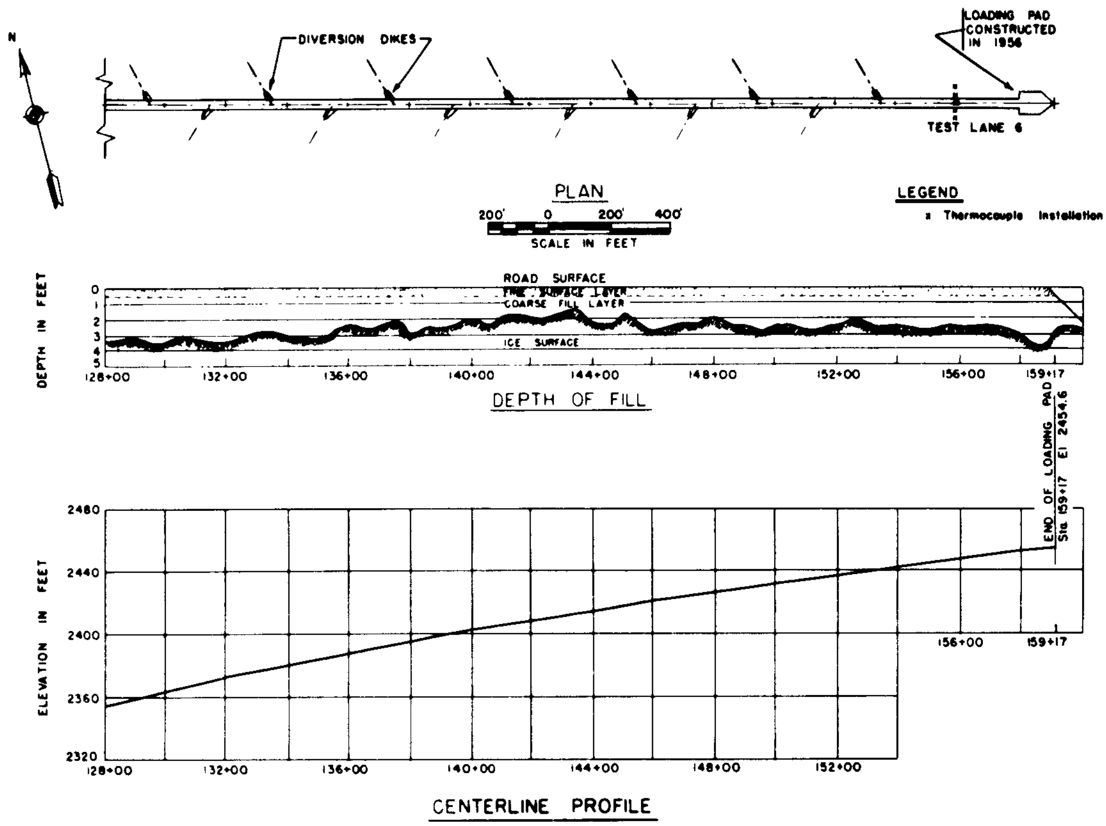


Figure 58. Plan and profile, Ramp Road, September 1957, Stations 128+00 to 159+17.

ahead of road construction. Windrows of snow were placed to divert meltwater flow away from the road. To aid in this task, ditches were periodically cut in the snow cover with a grader to divert the flow into channels at some distance from the toe of road fill and from the area in which road fill was to be placed.

Road construction. Some experimental sections of road were constructed in 1955[6] to aid in determining the most suitable depth and type of fill for the Ramp Road. They were:

Stations 57 + 00 to 60 + 00	18 to 24 in. of silty gravelly sand on 6 in. of cobbles
Stations 60 + 00 to 63 + 00	12 in. of silty gravelly sand on 12 in. of cobbles and boulders
Stations 65 + 50 to 66 + 50	12 in. of crushed rock directly on ice surface

The performance of the first two sections was satisfactory except that in the early part of the season, when the fine soil became wet from melting snow and thawing soil, rutting under traffic was more prevalent in these sections than where the silty gravelly sand was only 6 in. deep over 2 ft of cobbles and boulders.

It was concluded that with the available soil, a 6-in. thickness of fine soil surfacing was preferable to a 12- to 24-in. thickness.

The third test section (12 in. of crushed rock placed directly on the ice surface) became saturated from meltwater and tended to displace under wheeled traffic. The surface became excessively

rough because of differential melt of the underlying ice. The section was finally filled with coarse material and surfaced with fine soil to bring it to the grade of the remainder of the road. The section was a failure, of course, but it was considered that a fair test had not been made. One disadvantage was that the section was only 100 ft long, and was situated in the road between fills 2-1/2 ft deep or more. Moreover, the crushed rock was crusher-run and not screened to eliminate fines.

The performance of the road constructed in 1955 indicated that a 2-ft fill of coarse material surfaced with 6 in. of fine material provided a stable road. In an average year that amount of fill would be enough to raise the road surface above the winter snow cover. These thicknesses were established as standard for the 1956 road construction, although variation was allowed where irregularities occurred in the ice surface. (See Figs. 57 and 58.) Gradation of the coarse material is shown in Figure 21, and of the fine material, in Figure 22. Width of road was continued at 30 ft with side slopes about 1:1. Compaction was by planned routing of the trucks and the D8 bulldozer engaged in spreading. The fine surfacing fill was placed 200 or 300 ft behind the coarse fill.

Figure 59. Dikes on Ramp Road to divert meltwater channel from toe of road. Note that channel in foreground has returned to toe of road (19 July 1958).

Dikes. Based on conclusions made in 1955, "dikes" were constructed along the new road (Fig. 59). These dikes were short sections (30 to 40 ft long) of gravel fill extending out from the road at an acute angle to the road alignment in a downhill direction. Their purpose was to direct the meltwater flow away from the toe of road fill. The 1956 dikes served a dual purpose in that they were used for turnaround pads by the trucks during the construction period (Fig. 60). Partly for this reason, they were spaced about 200 ft apart on alternate sides of the road, or about 400 ft apart on each side. As in 1955, the dikes were generally effective in diverting meltwater flow from the road; however, their length and spacing require some consideration. Toward the end of the road, where the ice surface slopes toward the road (Fig. 2), the spacing and/or length of dike was not adequate, and the channel was able to return to the toe of fill before reaching the next dike. This could be remedied by spacing the dikes closer together or by lengthening them. Thus, the spacing of 400 ft and length of, say, 35 ft are adequate where no appreciable slope toward the road exists; closer spacing and/or greater length is required when the adjoining surface does slope toward the road. If such a slope is great enough, dikes may not be practical as the water would simply flow around them, returning almost immediately to the toe of road fill.

Figure 60. Dikes on Ramp Road to divert meltwater channels from the toe of road, looking south (15 Aug 1957).

Loading pad. The Ramp Road is used extensively during the summer to transfer equipment and supplies from trucks and other wheeled vehicles to the

cargo sleds which comprise the tractor-hauled trains operating on the ice cap. For convenience, a pad (see Fig. 58) was constructed at the end of the road to provide storage area, space for a small shelter, and room to operate a crane or other equipment for loading operations. The end of the pad was pointed to direct the meltwater flow away from the fill. Depth of fill beneath the pad was increased to about 3-1/2 ft for greater stability.

Test Lane 6. At Station 155+00, a series of thermocouples was installed (see Figs. 58 and 61) to obtain subsurface temperatures for comparison with temperatures obtained at lower elevations in Test Lanes 5 (Sta 80) and 3 (Sta 10). Although designated Test Lane 6, no change in depth of fill or other deviation from the standard design was incorporated at this location.

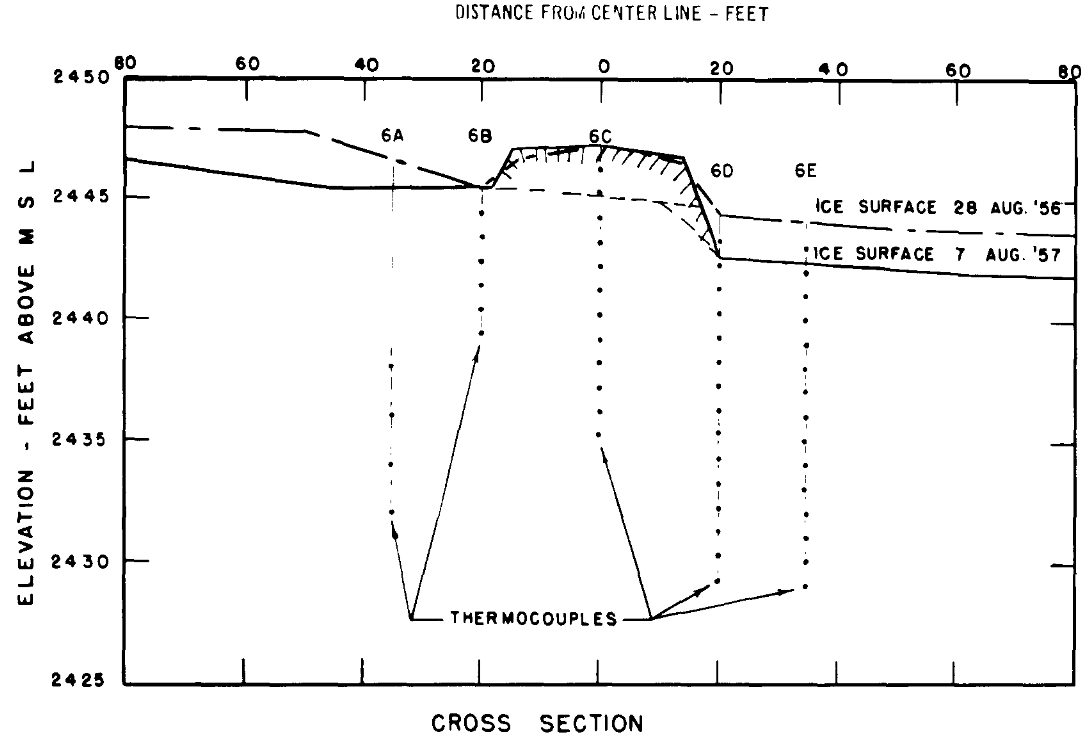


Figure 61. Thermocouple installation, Test Lane 6.

Dust palliatives. As soon as the snow cover had melted from the road surface and shoulders, the gravel roads quickly dried, at least on the surface, and usually remained dry for the remainder of the thaw season (precipitation is normally very light in the summer). As previously described, this tends to create a dirty ice surface as dust is blown over the area. In addition, the loss of silt and sand caused by traffic and wind is detrimental to the wearing qualities of the road. It is obvious that treatment of the road surface with dust palliatives would help to correct this situation. In 1956, trial was made of the use of (a) water, (b) waste arctic-grade lubrication oil, and (c) diesel oil. The use of water was ineffective; in the dry air, constant wind, and 24-hour daylight, evaporation was rapid and the water had to be reapplied at too frequent intervals to be practical.

The waste lubrication oil had accumulated for some time from maintenance of vehicles and construction equipment and amounted to about 300 gal. This was spread, using a tank and gravity-flow spreader bar. It was found that 0.3 gal per sq yd was required to cover the road surface, i.e. 300 gal of oil covered only 300 ft of road. To cover the entire road length, a greater amount of oil

would be required than would probably ever be available. However, the oil was an effective palliative.

The diesel oil was also applied at the rate of 0.3 gal per sq yd, and 10,000 sq yd of surface, from Stations 0+00 to 30+00, was treated. Investigation showed that the oil penetrated the surface 4 to 6 in. in one day. After 2-1/2 weeks, the diesel oil was still adequately controlling the dust; however, at that time it was necessary to resurface this stretch of road because of damage from a severe rainstorm. Sufficient diesel oil to re-treat the road was not available. It was concluded, however, that the application of diesel oil at the rate of 0.3 gal per sq yd is an effective and practical method of dust control.

Evaluation of Ramp Road. During the 1956 work season, observations were made of the performance of the first 9700 ft of road constructed in 1954-1955. In general, performance was adequate. The road remained trafficable to heavy (20 ton) trucks which averaged 100 passes per day, to light (2-1/2, 3/4, and 1/4 ton) trucks, and to many incidental passes of tractors, weasels, and truck-trailers. Maintenance consisted of frequent passages with a motor grader, and in one instance 700 ft of road was resurfaced with fine gravel. A few loads of gravel were dumped on the shoulders at scattered locations where slumping occurred.

One instance of road failure occurred in 1956 at approximately the same location and for the same reason as that which occurred in 1955.[6] Near Station 14+00, a small area suddenly became wet due to an apparent upward seepage of water from beneath the fill. A CBR value of 1.9 was measured (average of six tests) on the surface. The soil was generally too wet to measure unit weight or moisture content, but one value was obtained that corresponded to 3 CBR, i.e. 136 lb per cu ft dry density and 7.8% moisture content. Over an area approximately 10 ft square, the normal traffic, including 1/4-ton jeeps, produced ruts up to 5 in. deep. More serious damage might have resulted if the underlying coarse fill material had not been present. It is surmised that melting snow on the shoulders of the road produced a meltwater flow within the coarse fill. At the point of failure, the drainage of the coarse fill was greatly impeded by fines which had filled the voids. In the following year (1957) with less snow cover and with the road surface perched higher above the ice, failure did not recur.

In 1957 careful observations were made of the performance of the entire Ramp Road from Station 0+00 to 159+00. Considerable repair work was necessary to keep the road in condition to support traffic. The unusually warm summer of 1957 produced conditions that severely tested the road, and its performance was generally excellent, with a reasonable amount of maintenance.

Effect of ice cracks. On 11 June 1957, 18 cracks in the road fill were observed between Station 25+00 and the end of the road. Cracks ranged from hairline to 2 in. wide and were apparently extensions of cracks in the underlying ice. No damage to the road occurred as the cracks closed in a few days.

Effect of ablating ice surface. As noted in paragraph 26, the ice surface adjacent to the road ablates in the thaw season. In 1957, the ice losses were very great, reaching over 10 ft in some places. Beneath the gravel fill, ice melt was negligible. The differential ice melt between the ice beneath the road and that adjacent to the road results in an increased perching of the road. Perching is the primary limiting factor in the life of the road. Table XIII lists the heights of the ice ridge at various stations along the road. Tentative rates of perching based on performance to date have been calculated and are listed. Note that at Station 36+50 the road would rise 62 ft in 10 years and, with its 1957 height, would then be 80 ft above the ice surface. The sides of the ice ridge on which the road fill is perched have no protection from thawing, except for such gravel as falls from the slumping shoulders. Therefore, the slumping is increased by melting of the sides of the ice ridge. At the height of the warm season there may also be some erosion of gravel by flowing meltwater.

Table XIII. Perching of Ramp Road, 17 August 1957

Station	Average Height of Road Above Ice Surface ft	Depth of Fill ft	Height of Ice Ridge ft	Age of Road year	Rate of Perching Development ft/year
13+00	21	3.5	17.5	3-1/2	5.0
36+50	18*	2.5	15.5	2-1/2	6.2*
52+30	13	2.5	10.5	2-1/4	4.7
90+00	11	2.5	8.5	2	4.3
155+00	5	2.5	2.5	1	2.5

* Perching is increased at this station by upward movement of ice.

The road narrowed steadily each summer, and dangerous, steep slopes developed on each side of the road. Road damage was greatest where perching was highest, i.e. at the hummock area near Station 32+00 (Fig. 62). It was necessary to add fill to the shoulders at the places where damage was greatest to bring the road to its full width and to help protect the ice ridge from melting.

Figure 62. Road profile looking north at about Stations 27+00 to 37+00. Dark-colored portion of side slope of road indicates underlying melting ice has wet the covering gravel. Note ice hummocks in foreground (29 July 1958).

The road from about Stations 20+00 to 60+00, already (in 1957) high above the ice surface, will be 60 to 100 ft high in 1967 and maintenance will be impossible (see Fig. 39). Apparently, the road cannot be maintained in this area for as long as 10 years without the aid of berms to slow melt of the ice surface and degeneration of the ice ridge under the road.

Beyond Station 60+00, the vertical (downward) movement is small, and the main concern is with the ablation of surrounding ice. It will be noted that ablation in this area is considerably less than in the first 6000 ft (Stations 0+00 to 60+00), and even in 10 years would not be prohibitive.

The foregoing statements regarding the life of the road are made with the assumption of a more or less dirty ice surface. If the ice could have been maintained in its natural

clean state, the ablation would have been much less and the life expectancy of the road correspondingly longer.

Effect of ice movement. As noted in paragraph 23 the ice and road move generally downhill as much as 11 ft per year in the area above the hummock zone or Station 32+00. This means there is an annual shortening of the road of about 11 ft, plus some sideways movement, particularly near the upper end of the road. These movements have very little effect on the road. It is apparently sufficiently flexible to adapt to the movement with only slight humping and waviness in alignment. The greatest effect of ice movement occurs at about Station 32+00 where upward movement is greatest. Here the movement adds as much as 3 ft per year to the elevation of the road surface above the ice. In addition, the upward movement creates a sizable hump in the road. Since construction in 1955, the slope of the road from Stations 29+00 to 32+00 has increased from 7.2 to 8.4%, a rate of about 0.6% per year.

Surface wear. It has been noted that the surface of the road becomes quite dry as the thaw season progresses. Much dust results and is dispersed by wind and traffic over the surrounding ice surface, causing a loss of from 6 to 9 in. of surfacing soil. This, plus the normal wear of heavy traffic, made it necessary to resurface sections of the road. From 9 to 12 in. of gravelly sand, about 7000 cu yd, was added over most of the first 2 miles of road.

Berms

38. The 1955 investigations established the value of constructing a blanket or berm of soil, 1 ft or more thick, extending from the toe of road fill, to decrease the amount of ice melt and thereby prolong the life of the road.

1955 test berms. Experimental sections of berms were constructed at three positions on the road as follows:

Date Constructed 1955	Constructed Between Stations	Berm	
		Type	Material
11 July	22+00 and 23+50	1 ft thick, 25 ft wide	Random gravels*
11 July	23+50 and 24+50	4:1 slope	Random gravels*
11 Aug	53+50 and 54+00	4:1 slope	Random gravels*
11 Aug	54+00 and 55+00	1 ft thick, 40 ft wide	Random gravels*
16 Aug	62+70 and 63+65	3 in. thick, 6 in. thick, and about 12 ft wide	Crushed rock**

* See Figure 23 for gradation.
** See Figure 25 for gradation.

Figure 63 shows profiles of the berm constructed between Stations 22+00 and 23+50 after approximately 1 year. More than 3 ft of ice had melted from the uncovered surface, but the berm was nearly undisturbed. An additional 3 ft of perching of the road fill would have caused the shoulders to slough. Further observations of this berm were not made because a new 50-ft berm was constructed in the same place in August 1956.

Measurements were not made of the movement of the random gravel berm between Stations 53+50 and 55+00, but observations of the performance of this section indicated that it provided substantial protection to the road fill in spite of heavy melting of the surrounding ice surface. The progressive subsidence of the edge of section having the 4:1 slope was observed to be slower than that of the 1-ft-thick, flat section. The amount and position of soil in the 4:1 slope section provided greater protection

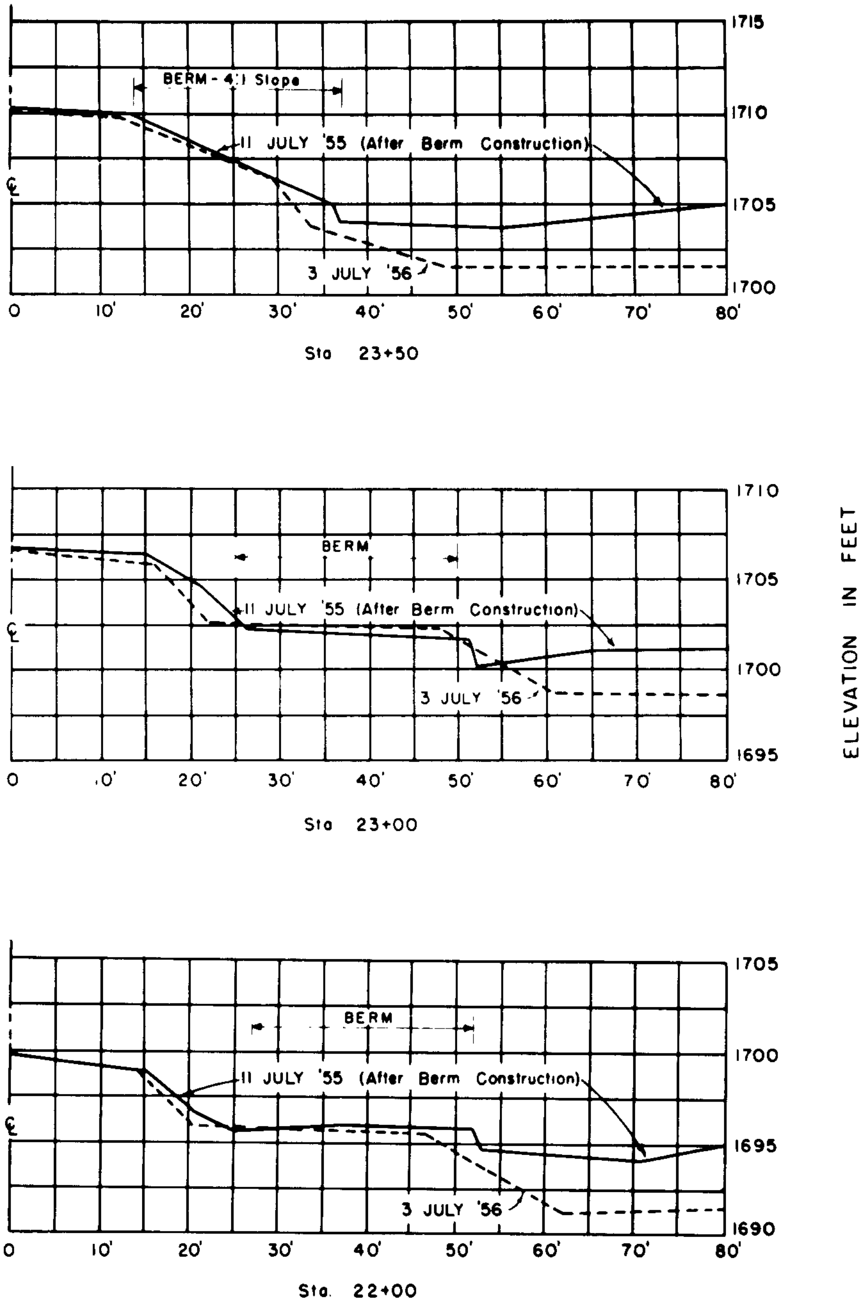


Figure 63. Comparison of original profiles of test berms, constructed 6 July 1955 for shoulder protection, and profiles 1 year later.

of the resulting exposed ice slope. However, a simple 4:1 slope on a 2-1/2-ft-thick road fill was not wide enough to provide protection for a significant time.

Figure 64 shows cross sections of the crushed rock berm between Stations 62+70 and 63+65 on 5 July 1956. Although there had been only a short period of thaw since its construction on 16 August 1955, and melt of the ice surface was only 1 to 2 ft, it is apparent that the thin (3 and 6 in.) layers of crushed rock were inadequate to protect the ice from excessive melting. Meltwater streams

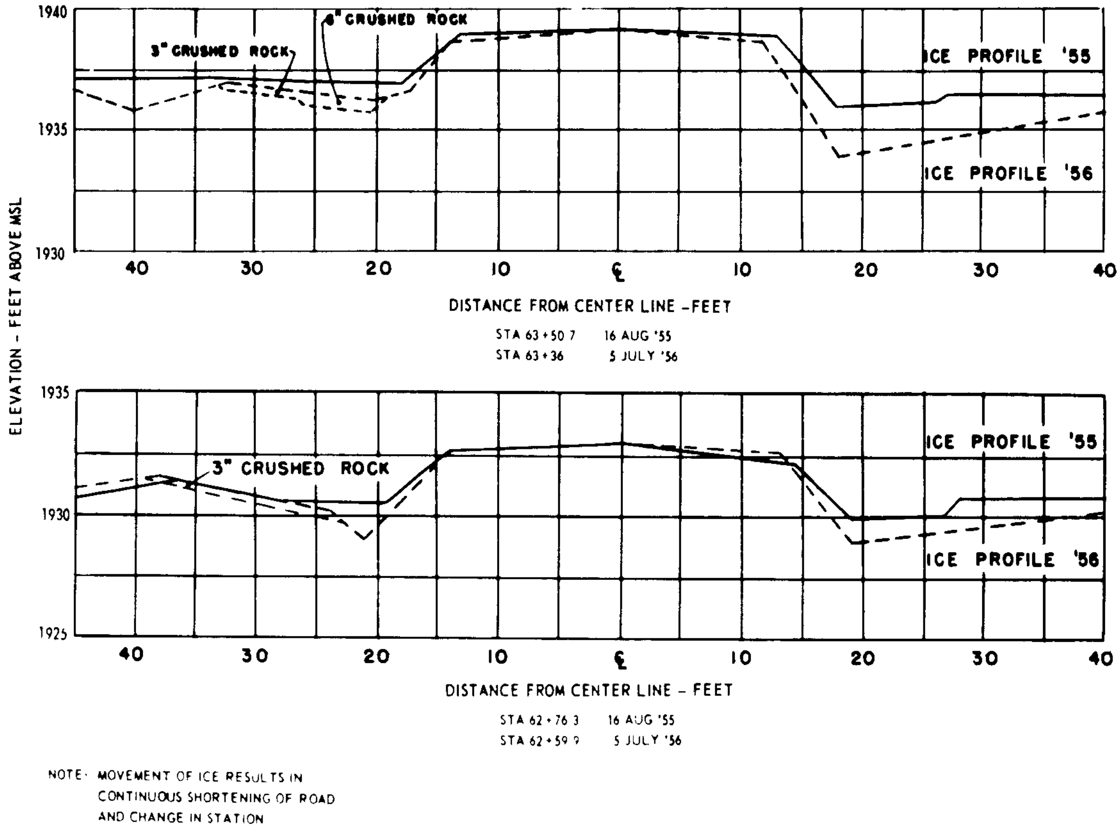
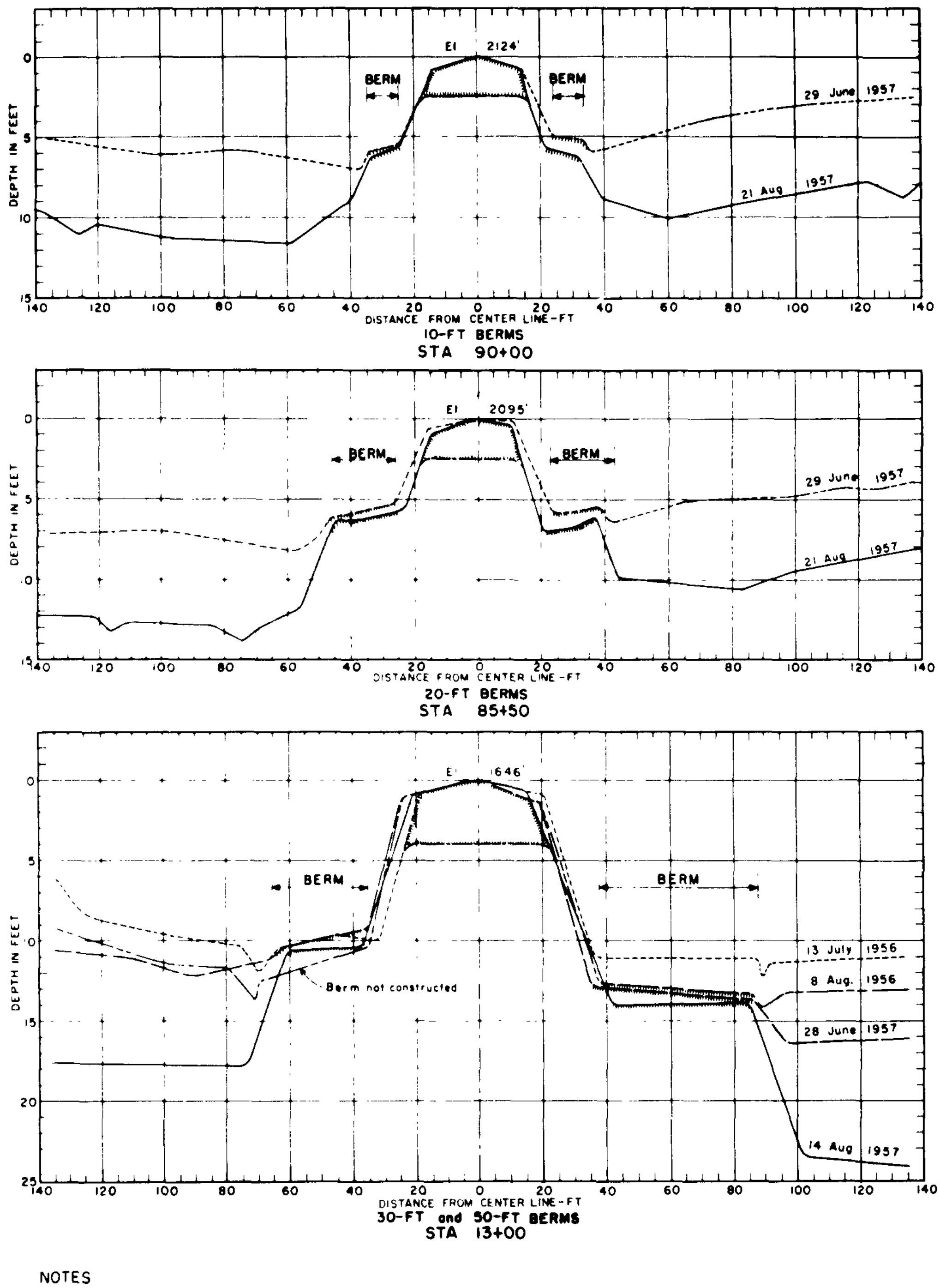


Figure 64. Crushed rock test berm, 1955.

easily overflowed the berm and developed a sizable channel at the toe of road fill. A large amount of the crushed rock was washed from the berm.

1956 operational berms. On the basis of the performance of the 1955 test berms, the first 3000 ft of Ramp Road was equipped with berms in 1956 to protect the road fill from imminent failure by excessive perching. On the south side of the road, from the edge of the ice ramp to Station 30+00, the berm was constructed 50 ft wide and a minimum of 1 ft deep. On the north side, from the edge of the ice ramp to the intersection of Ramp and Transverse Roads, the berm was constructed 30 ft wide and a minimum of 1 ft deep. Figure 2 shows the location of the berms. A random-type gravel (see Fig. 23) from Borrow Area AA was used. Berm construction was carried on throughout the entire 1956 work season concurrently with road construction. The south berm was constructed first and the north berm second; construction was completed the first week in September 1956. Figure 65 shows cross sections through both berms at Station 13+00 at various intervals from 13 July 1956 to 14 August 1957.

The degree of protection furnished the road is obvious. In the period of measurement, the uncovered ice surface melted about 12 ft on the south side and about 8 ft on the north side. If this had occurred at the toe of road fill, it is quite possible the road would have failed. It will be noted that there was some melting of the ice beneath the berm; 1 ft of gravel is not sufficient to completely protect the ice. However, the amount of melt was greatest in the first year (less than 2 ft) and negligible in the following year (about 0.5 ft). It is estimated from Figure 65 that about 2 ft of berm width would be lost per year at this location (Station 13+00) on the ramp.



NOTES

Stations refer to Ramp Road stationing (see Fig. 2)

Movement of the ice beneath the road results in upward or downward movement of the road surface. To show the correct relation of top of road to top of berm and ice surface, the center line of road has been assumed to remain at the same elevation.

Road stations listed were true stations at the close of the 1957 thaw season. Horizontal movement of the ice results in constant shortening of the road.

Elevations are in feet above mean sea level.

Figure 65. Cross sections of berms, TUTO Ramp Road.

1957 test berms. Although the usefulness of berms in protecting the roads on ice had been amply demonstrated, the proper berm dimensions to afford protection for a given length of time and at any location along the road had not been determined. Therefore, two sections of test berms were constructed in 1957 between Stations 83+00 and 93+00, slightly more than halfway to the end of the Ramp Road (Fig. 66). Each section was 500 ft long and 1 ft deep; one section was 20 ft wide and the other 10 ft wide (see Fig. 67). The gravel used was coarse, similar to that used on the base course of the road fills. The gradation was as shown in Figure 21 for borrow pit L, except that an attempt was made to include a larger percentage of gravel sizes than was used in the roads. The resulting material had a maximum size of 24 in. About 70% (by weight) was greater than 2 in. and about 80% was greater than 3/4 in. The construction of the berms was completed by 29 June 1957.

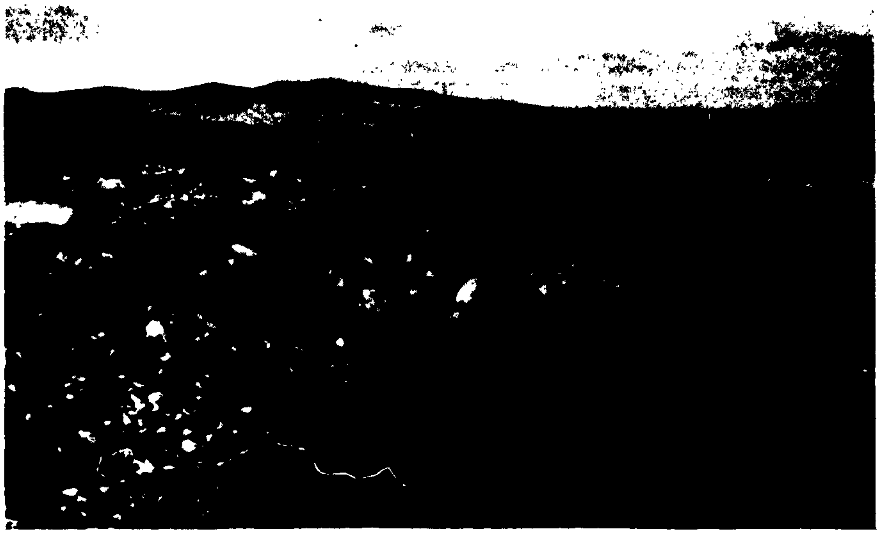


Figure 66. Berm, 20 ft wide, at about Station 88+00, looking west (7 Aug 1957).

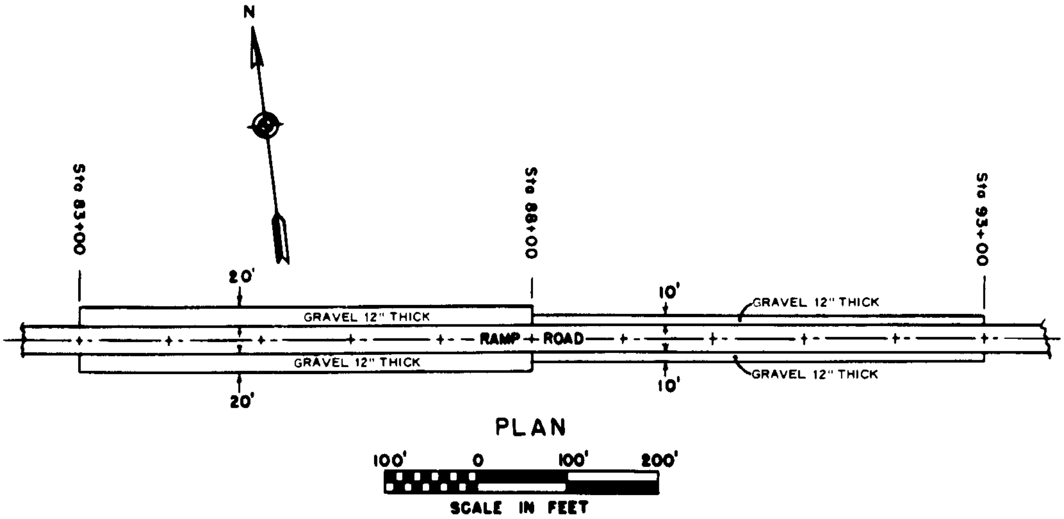


Figure 67. Test berms, 1957.

Figure 65 shows representative cross sections of the 10-ft- and 20-ft-wide berms. The position of the berms at the close of the 1957 season (21 August) may be compared with the "as-built" position (29 June). In that period, the adjoining ice surface melted 5 to 6 ft, whereas the ice beneath the berms melted 1-1/2 ft (note that melt beneath the berms is greater on the south side than on the shaded north side). Therefore, substantial protection was afforded the toe of road fill in the first season. A large amount of ice melted beneath the berms, particularly beneath the 10-ft-wide berm where it appears that after one more thaw season this berm might lose its identity because of gravel spilling down the slope.

Analysis of results. It was noted in the cross sections at Station 13+00 (Fig. 65) that thaw beneath the berm is greatest the first year after construction. The fill when placed is, of course, in a thawed condition, and heat flow to the ice can start almost immediately. In the second year the berm fill would commence the thaw season in a frozen state, probably containing a great quantity of ice, as the fill generally would be very wet when freezing commenced. In the second year, much time and heat would be required to thaw the soil blanket before the underlying ice would begin to melt. Thus, it could be expected that melt beneath the berm would be substantially less the second year, other conditions being equal.

Between 1 and 2 ft of berm width was lost in the 1957 thaw season, with the greatest loss on the south side. After the first year, about 1 ft of width per year might be lost. There was an unusual amount of ice melt in 1957, so this value may be less in a normal season.

Using random-type gravel, a berm thickness of 1 ft is satisfactory, especially after the first year.

The performance of the 10-ft-wide berm cannot be considered adequate, apart from the melt of ice beneath it. The fill developed a slope outward and tended to slough off down the ice slope. It is concluded that a 10-ft-wide berm is unsatisfactory under most conditions.

Tentative values, based on only 1 or 2 years of measurement (1 year was abnormally warm), indicate that berms in the first 1300 ft of the Ramp Road lose about 2 ft of width per year, and berms located about 8500 ft from the edge of the ice lose about 1 ft of width per year. Thus, on this basis, berms to protect the road for 10 years should be 20 ft wide for the first 1/4 mile of road, decreasing to 10 ft wide at about 1-1/2 miles. However, it is considered probable that the rate of raveling of the edge of berm will increase as the ice ridge grows higher; therefore a minimum width of 15 ft is considered necessary. Accordingly, a minimum of 30 ft for the first 1/4 mile, decreasing to 15 ft at about 1-1/2 miles, is recommended for 10-year life.

Conclusions concerning the dimensions and characteristics of berms should be considered as preliminary only. Further observation of the performance of existing berms is required to establish criteria.

Thin-fill-road test section

39. In the search for more economical and simpler methods of constructing roads on ice, the feasibility of using thin fills of crushed rock was investigated. One such fill was tried in 1955. It consisted of 12 in. of crushed rock (crusher-run) in a 100-ft length of the Ramp Road. The section failed, but as stated earlier, the trial was considered inconclusive because the section was too short, was located between the deeper 2-1/2-ft fills of the regular road, and the crushed-rock gradation was unsuitable. In 1957, therefore, a special test section was constructed and tested.

Construction. Figure 68 shows the layout of the test section. Provision for traffic-testing was made by constructing ramps to connect with the main road at each end of the test section. In

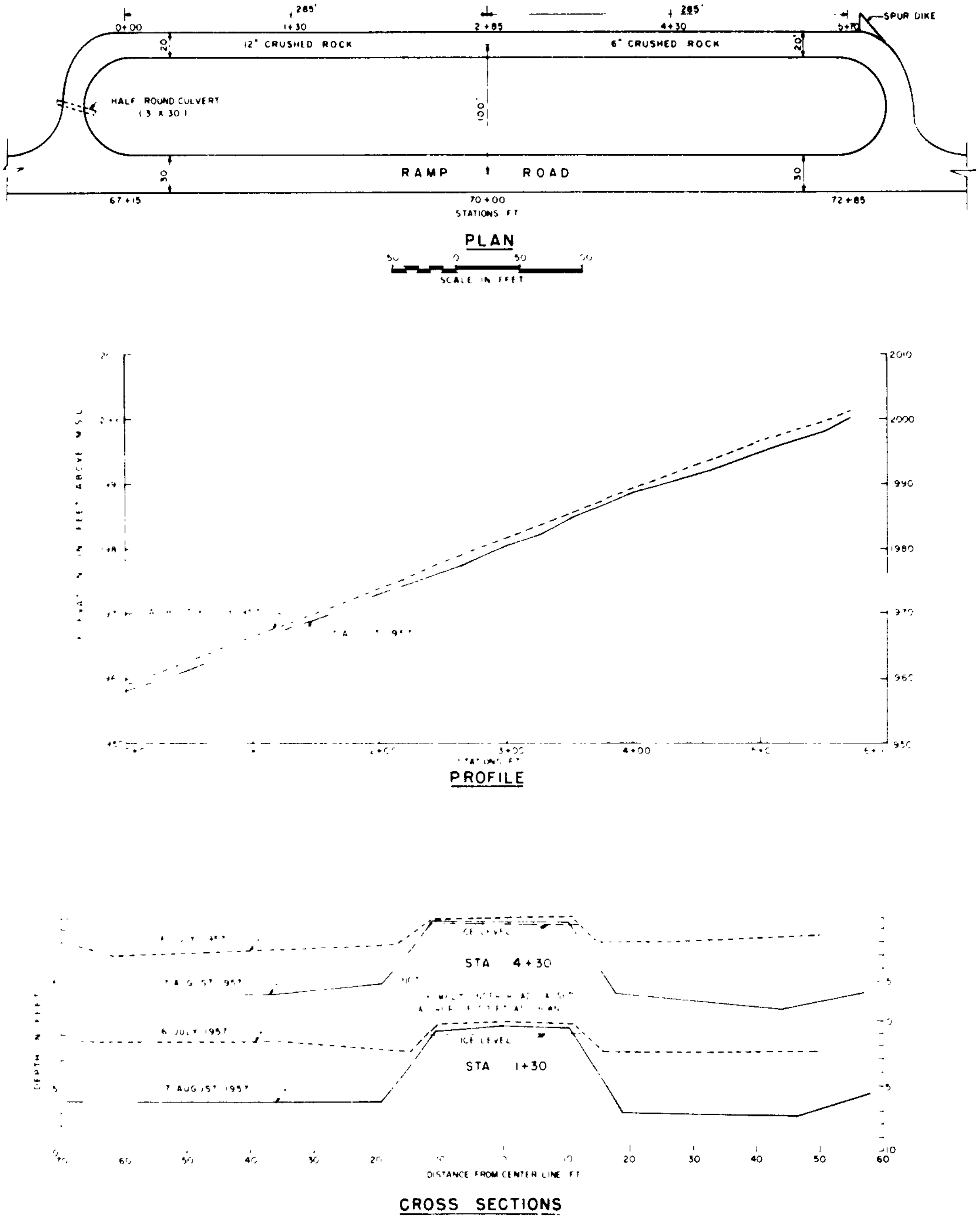


Figure 68. Crushed rock test section.

addition, all possible precautions were taken to prevent the occurrence of abnormal erosion from flowing meltwater. As shown in Figure 68, the outside toe of fill was protected by the construction of a small dike to divert the flow away from the test road. A half-round, 36-in.-diameter, corrugated metal pipe was placed in the fill of one access ramp to drain off meltwater accumulating in the area between the test section and the main road. Fill material was crushed and screened rock (mostly gneiss and granite) graded as shown in Figure 25 for 1957 material. Thickness of fill was nominally 12 in. for 300 ft and 6 in. for 300 ft, as shown in Figure 68. The thickness was varied slightly, always in

the direction of greater than nominal, to smooth the uneven surface of the ice. Upon completion of the crushed-rock fill, the surface was choked with screenings from the rock crusher. Gradation of screenings is shown in Figure 69. The fills were carefully compacted with a motor grader and the D8 bulldozer. Water was added to aid in compacting. Immediately before the traffic test, tests on the in-place material showed an average (6 tests) dry density of 137 lb per cu ft in the top 6 in. and an average moisture content of 3.6%. The range of dry densities was 127.0 to 143.6 lb per cu ft; range of moisture contents was 3.0 to 4.4%.

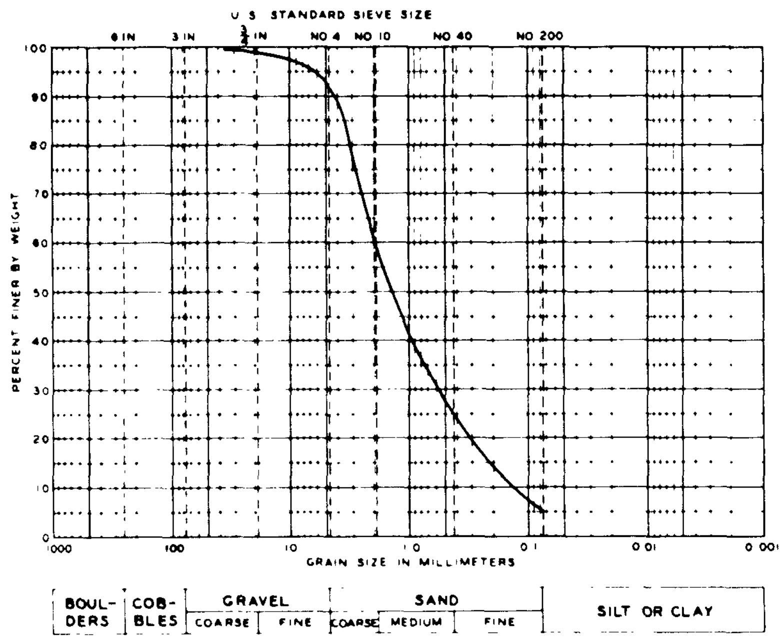


Figure 69. Gradation of crusher screenings, thin-fill test section.

Traffic tests. A count of traffic on the main Ramp Road showed that the following accelerated traffic would simulate 1 months normal traffic in 3 days:

Truck and tractor each working alone:

240 passes of truck, dump, 6×6, w/5000-lb payload = 16,850 lb
60 passes of tractor, D8, w/standard treads and dozer = 41,600 lb

Truck and tractor working simultaneously:

480 passes of truck, dump, 6×6, w/5000-lb payload = 16,850 lb
120 passes of tractor, D8, w/standard treads and dozer = 41,600 lb

Three tests were conducted: on 8-10 July, 25 July-2 August, and 13-15 August.

The first traffic test was conducted immediately after the section was finished, which was about 10 days after the first fill was placed. Figure 68 shows that on 6 July the road was already perched above the ice surface about 1-1/2 ft; melting beneath the fill had started. The first traffic test caused wet spots to appear on the surface; the wet areas tended to be soft. The section having a 6-in.-thick fill had more and larger wet areas than the 12-in.-fill section. Some disturbance of the surface was caused by the grousers of the treads of the tractor - a mixing of the crushed rock and

screenings and a tendency to crush the rock (Fig. 70). However, the road was passable at the end of the first test representing 1 month of normal traffic.

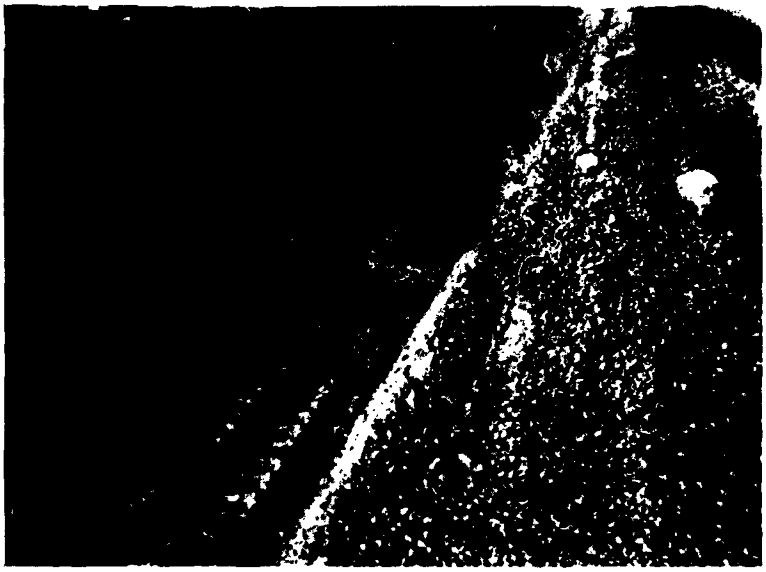


Figure 70. Surface of crushed-rock test road after 180 passes of dump truck weighing 16,850 lb (July 1957).

At the start of the second traffic test, the road was perched 2 to 3 ft above the ice surface. Melting beneath the fill continued. Pumping of water to the surface continued with traffic until the 6-in.-fill section was completely wet and the 12-in.-fill section had several wet areas (Fig. 71). Wear and/or compaction of the center area of road created a concave cross section and a number of potholes. However, at the end of the second test both sections were passable without rutting.

Figure 71. Meltwater on the surface of crushed-rock test road from melting ice beneath the fill (July 1957).

At the time of the third test, the road was perched 5 to 6 ft above the ice surface. Approximately 0.3 ft of ice had melted beneath the road fill, and the fill was almost saturated. Melting of the sides of the ice ridge under the road had caused considerable slumping of the shoulders. At the end of the traffic test, the surface of the crushed-rock fill was waving badly. The 6-in.-fill section was commencing to rut and was close to complete failure. The 12-in.-fill section had two low places where water ponded, shoulders were slumping badly, and potholes were conspicuous; however, rutting had not commenced. There was evidence of degradation of the crushed rock over the entire surface.

Analysis of results. It was demonstrated that thin (up to 12 in.) fills of crushed rock are unsatisfactory for roads on the ice where there is substantial ablation in the thaw season. The melting of ice results in excessive water in the fill and consequent reduction in strength and stability. The ablation of the adjoining ice surface results in excessive slumping of the shoulders. Six-inch fills of crushed rock might be feasible where there is no melt, or very slight melt of the ice in a thaw season, but the low height above the ice surface might result in excessive snow cover and plowing problems. Performance of the test section should be observed during one complete thaw season to confirm the findings made in 1957, when the test section was subjected to only approximately half a thaw season, and to further evaluate the feasibility of the use of thin fills on ice.

Summary

40. About 2200 ft of Transverse Road, 30 ft wide, was constructed in 1956, at an angle of about 60 degrees to the direction of meltwater flow. Depth of fill was 3 ft, consisting of 2.5 ft of coarse material and 0.5 ft of fine material. This road remained stable and trafficable throughout the 1957 season, except at culvert locations where erosion from meltwater flow after failure of the culverts and ablation of the adjacent ice surface made it necessary to replace slumping shoulders with additional gravel. Settlement of the road surface occurred where there was piping through the fill around the culverts, and some additional surfacing was required.

Placement of a test section of gravel fill on compacted snow showed such a procedure to be feasible, but erosion of the compacted snow by flowing meltwater occurred, with consequent settlement of the road fill.

A section of road was prevented from sliding on a steep ice slope by using a deep fill to prevent thaw from penetrating to the ice surface and by keying the gravel fill to the ice with trenches blasted in the ice surface.

Seven culverts, consisting of half-round, 36-in.-diameter, corrugated metal pipe bridging a natural meltwater channel, were installed in the Transverse Road in 1956. All seven culverts failed to perform adequately before the end of the 1957 thaw season because of (a) insufficient capacity, (b) blocking by snow, ice, and soil debris, (c) collapse after supporting ice was eroded, and (d) perching above the flow line.

In 1957, a pad was constructed in front of the entrance to the ice tunnel at the end of the Transverse Road. It was found feasible to excavate ice to a desired grade by blasting and clearing successive layers and to then construct a stable pad by placing a fill of 2 ft of coarse material and 0.5 ft of surfacing material on the ice surface.

The portion of the Ramp Road constructed in 1955 with a 2-ft fill of coarse, heavy soil and a surfacing layer of 0.5 ft of finer soil continued to be usable throughout the 1957 thaw season. Test sections of road having 1 and 2 ft of fine-soil surfacing showed a tendency to rut under traffic during the early part of the season when the surface was wet from melting snow and thawing soil.

Snow deeper than 1 ft was plowed from the ice surface before gravel fill was placed. Plowing

operations included the placing of windrows of snow and the cutting of channels in the snow to divert meltwater flow away from the area of road construction.

In 1956, a new section 6200 ft long, 30 ft wide, and approximately 2.5 ft deep was added to the Ramp Road. Alignment was parallel to the direction of meltwater flow, except for the last 1000 ft which crossed the flow at a slight angle. The end of the road (Station 159 + 00) is in the zone of transition between ablation and accumulation.

At the close of the 1957 season, the Ramp Road was perched approximately 21 ft at the start of the road and 2.5 ft at the end of the road above the adjoining ice surface. It was necessary to add gravel to the shoulders and slopes of the first 1.5 miles of road to repair damage by sloughing as the perching increased. The rate of perching since construction ranged from 2.5 to 6.2 ft per year.

A hump in the road, caused by differential upward movement of the ice, occurred at about Station 32 + 00. The slope of the road between Stations 29 + 00 and 32 + 00 increased from 7.2 to 8.4% in 2 years following construction.

Erosion of the road, which was aligned more or less parallel to the direction of meltwater flow, was successfully minimized by the construction of dikes that extended from the road in a downhill direction. The dikes were 30 to 40 ft long and spaced 400 ft apart on both sides of the road. This spacing and length was satisfactory, except where the ice surface sloped toward the road; in that area longer dikes and/or closer spacing was needed.

Diesel oil spread at the rate of 0.3 gal per sq yd was an effective and practical dust palliative. Dust spread over the ice surface increased the rate of ice melt, and the loss of fines from the road surface reduced the ability of the surface to withstand the wear of traffic.

Cracks in the road fill resulting from cracking of the underlying ice had no detrimental effect on the gravel roads.

A 1-ft-thick (minimum) blanket or berm of gravel was demonstrated to be an effective method of protecting gravel-fill roads on ice from sloughing and slumping due to excessively high perching above the surrounding ice surface. The ice melt beneath the berms was approximately 25% of that of the uncovered ice in the first year (the year the berms were constructed) and less than 5% in the second year.

The berms at Station 13 + 00 lost approximately 2 ft from their outer edge in 1 year, and the berms at Station 83 + 00 lost approximately 1 ft of width in 1 year. Experimental 10-ft-wide berms developed an outward slope and a tendency to lose gravel fill by sliding. Their performance was judged to be unsatisfactory. Based on Ramp Road conditions it was concluded that berms should be 30 ft wide for the first 1/4 mile of road, decreasing to 15 ft wide at about 1-1/2 miles from the beginning of the road, for 10-year life.

Crushed rock, in thin layers, was unsatisfactory for the construction of berms because of its poor insulating qualities and its tendency to be carried away by rapid meltwater flow.

A test road consisting of 300 ft of 12-in. and 300 ft of 6-in. crushed and screened rock, the surface choked with screenings, was traffic-tested three times in the 1957 thaw season. The traffic on the Ramp Road was counted and an equivalent coverage was established that simulated 1 months actual traffic in 3 days. In 42 days, the test road became perched on an ice ridge approximately 5 ft high, and an average of 0.3 ft of ice melted beneath the road fill. The melting ice saturated the fill, and under traffic, pumping occurred with soft spots appearing on the surface. After the third traffic test, the section with a 6-in. depth of fill was close to complete failure. The section with a 12-in.

fill still supported the traffic, but was in poor condition, with soft areas and potholes. Some wear of the crushed rock was observed.

VIII. BRIDGE

41. Figure 49 shows that the Transverse Road crosses a large meltwater channel at about Station 25+80 just below the point where it is formed by the junction of two channels. This channel is the largest encountered on the ramp and flows through a large gully (see Fig. 72). It was determined that a bridge would be necessary to carry the road across the gully because the quantity of flow was so great that a very large culvert would be required (experience with culverts on ice had been poor), and a very large quantity of fill would also be required to bring the road to a suitable grade. In addition, it was considered desirable to investigate methods of bridge construction on ice as an important adjunct to road construction. This construction was accomplished in the summer of 1956.

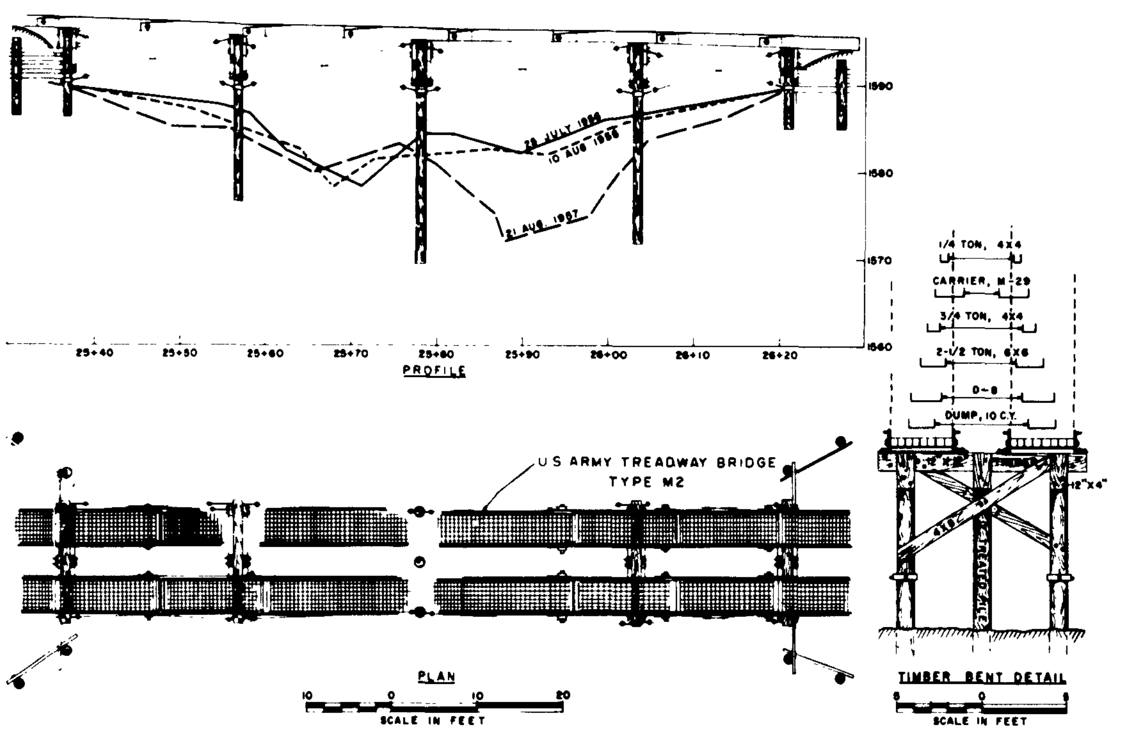


Figure 72. Pile-bent bridge.

Type and materials

42. In determining the type of bridge to be used, consideration had to be given to the availability of materials and skilled workmen. Moreover, for military purposes the bridge should be such that a small group of semiskilled men could erect it in a few days. A pile-bent type bridge was selected, the bents to support U. S. Army "Treadway" prefabricated bridging available at TUTO. A one-lane bridge was sufficient for the amount of traffic, and accordingly, only three piles per bent were necessary. Treated wooden piles, of 12-in.-minimum diameter at a point 8 ft from the butt end, and necessary wooden timbers were shipped to Greenland. The pile bents were assembled as shown in Figure 72.

Load capacity

43. The spacing of the pile bents was determined by the loads which it was desired to impose on the bridge and by the configuration of the ice surface. The heaviest mobile equipment which would use the bridge was a truck-mounted crane weighing about 29 tons. Treadway bridging with a span of 24 ft will safely support 40 tons.[1] It was found that three intermediate bents could be used, with spans between them of 20 and 24 ft (Fig. 72).

It was calculated that, using a stress value of 1600 psi, each pile was capable of supporting more than 50 tons in compression with an unsupported length of 15 ft. The adhesion strength of ice in which the piles were embedded has not been fully determined. However, assuming a conservative stress value (for creep) of 3 psi, the supporting capacity generated by skin friction was about 10 tons per pile when the piles were embedded about 15 ft. The ultimate capacity would, of course, be several times this value.

Thus, the capacity of the pile bents was ample when the dead load of the bridge on each bent was only about 7 tons and the greatest load imposed was the weight of the truck-mounted crane (29 tons) resting on the bridge a maximum of from 1 to 2 hours.

The longitudinal stress on the bridge developed by braking a 30-ton vehicle traveling at 15 ft per sec was calculated as about 21,000 lb. To offset this stress, a dead-man anchor was placed in the gravel fill at each end of the bridge (see Fig. 73). The anchor was a 20-ft-long, 12-in.-diameter pile buried 4 ft in gravel of 130 lb per cu ft density. The maximum resistance of which this anchor is capable was calculated as 31,200 lb.

Figure 73. Dead-man anchor constructed at each end of bridge to restrain longitudinal movement (8 Aug 1956).

Spacing of Treadway bridging

44. As shown in the diagram of Figure 72, the Treadway bridging was spaced in width to allow use by most of the vehicles available at TUTO. Only the M29 carrier (weasel) could not cross the bridge because its treads are too close together.

Construction

45. The construction of the Transverse Road was first completed to the bridge site to provide access for trucks carrying materials and for cranes and other equipment required to accomplish the work. The bridge was constructed by the civilian technicians and military personnel attached to the project, about six men. None of these men were trained in bridge construction. The fact that they could accomplish the job in a reasonable length of time and with a minimum of equipment is an indication of the feasibility of this type of bridge for military purposes. The bridge construction was completed in 19 working days between 19 July and 14 August 1956 (Fig. 74). Eight days were lost because of poor weather. It is estimated that with proper equipment, adequate personnel, and good weather, the bridge could have been constructed in approximately 1 week.

Figure 74. Bridge from west looking upstream. North bulkhead has not been backfilled (17 Aug 1956).

Installation of piles. The wooden piles were installed in holes drilled in the ice; the annular spaces were then backfilled with slush, which froze to hold the piles firmly. The bulkhead posts at each end were installed in the same manner, using short lengths of the 12-in.-diameter wooden piles.

Drilling in ice. The only available equipment for drilling holes in the ice was a modified posthole auger having a 5.5-hp, 2-cycle, gasoline motor and a 12-in.-diameter helical auger. The cutting blade was modified to adapt it to cutting ice, and the driving mechanism was adapted to allow the attachment of additional drill rod lengths for drilling holes to depths of 15 to 20 ft. Normally, the auger is hand-held and operated by two men who support it, control the cutting speed by means of a throttle, and raise or lower the auger as necessary. The latter operation could not be accomplished manually when the auger had to be raised higher than 6 or 7 ft, and experimentation with various methods was necessary to establish the most feasible procedure. The danger of the auger's freezing in the hole was so critical that the method of hoisting it from the hole had to be quite positive; that is, the pull had to be immediate, smooth, and straight. Using a tripod with a pulley, a hand winch, or

even the power winch on a truck was found unsuitable. However, a D8 tractor equipped with a boom and winch worked fairly well (Fig. 75).

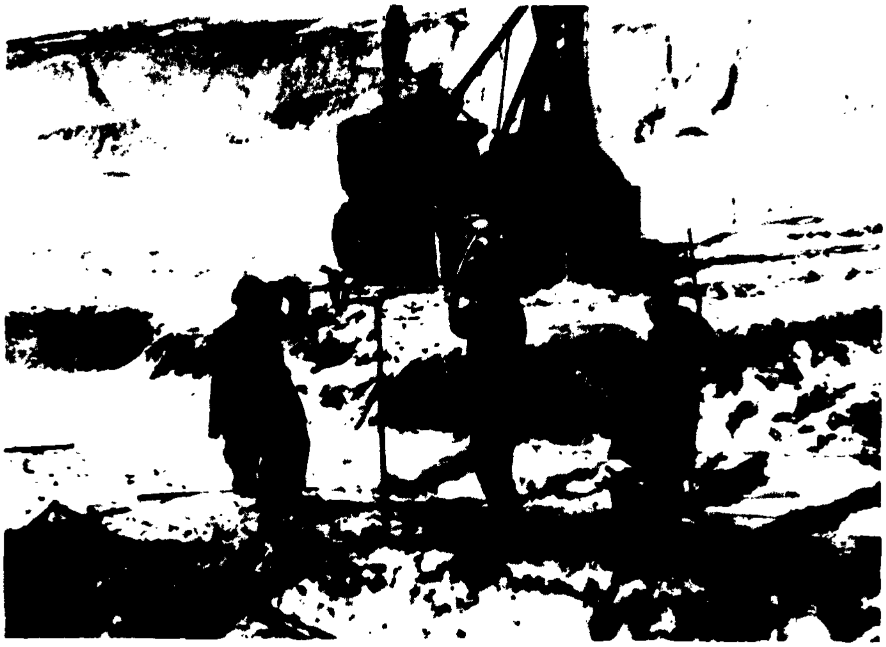


Figure 75. Drilling of holes in ice for piles. Note D8 tractor with boom used to raise or lower drill (7 Aug 1956).

Assembly. The south bulkhead was completed first and backfilled to provide a stable place from which to operate the truck-mounted crane. Piles were placed in the drilled holes as soon as two or three holes were completed to ensure that the holes did not close in or fill with snow or meltwater. After the first bent beyond the south abutment was completed and Treadway bridging installed, the crane could be moved forward on the first span and used in assembling the second bent. Timbers used in constructing bents and bulkheads were bolted together; holes for the bolts were drilled with a pneumatic drill. The Treadway bridge sections were lifted into place by the crane, and fastened to the bent cap timbers with 1/2-in. steel plates. The plates were installed so that the Treadway bridging was free to slide longitudinally but restrained from moving sideways (see Fig. 72).

As stated previously, anchors were constructed at each end of the bridge by placing a 20-ft length of 12-in.-diameter wooden pile in a trench that was cut in the gravel fill. Cables were fastened from the pile to the ends of the Treadway bridging. The trench was carefully backfilled and the gravel was compacted with the D8 bulldozer.

The bridge was braced for stiffness by adding diagonal cable stays between each bent; the stays were fastened to the wooden piles with improvised stirrups (Fig. 76).

It was obvious that ablation of the ice around the dark-colored wooden piles would be detrimental to bridge stability, and an attempt was made to paint the piles white; however, the creosote of the treated piles bled through the paint. Temporary protection against melting of the surrounding ice surface was obtained by laying scrap pieces of aluminum-faced plywood against the piles and on the

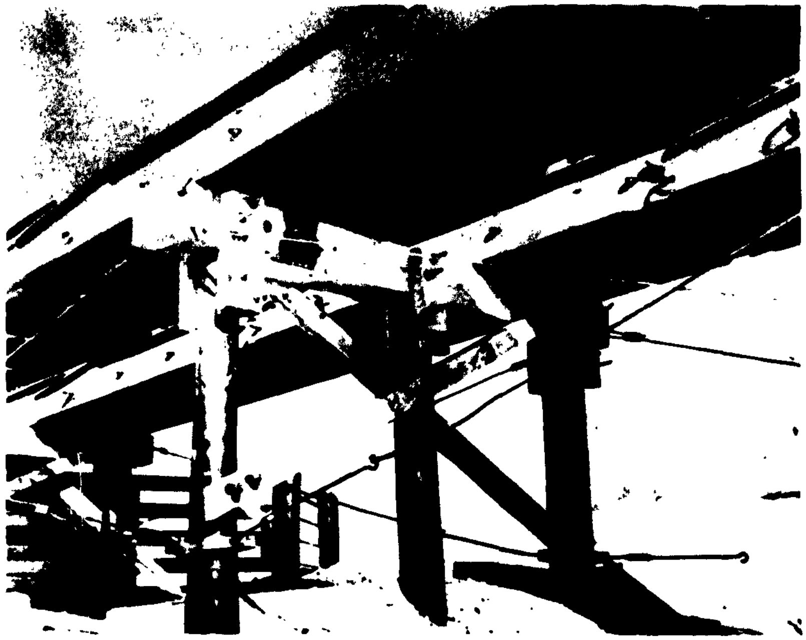


Figure 76. Wooden pile bent. Note stirrups and cable ties (17 Aug 1956).

ice surface next to the piles. A more permanent protection was obtained by surrounding the base of the piles with a gravel blanket held in place by a plank wall (Fig. 76).

Performance

46. The profile in Figure 72 shows the level of the ice before (25 July 1956) and after (10 August 1956) construction of the bridge. Also shown is the profile of the ice surface beneath the bridge at the end of the 1957 thaw season. It will be noted that the channel had eroded more than 11 ft in depth in approximately 1-1/2 thaw seasons (Fig. 77). At that time, the piles were still firmly

Figure 77. Pile-bent bridge showing ice erosion in channel (9 Aug 1957).

embedded in the ice to nearly their original depth. However, it was obvious that continued erosion at the same rate would undercut the piles.* The original channel that the bridge spanned drained a relatively small area of the ice cap adjacent to the moraine plus one channel that originated above the moraine. With the failure of the culverts through the Transverse Road (see paragraph 36), the entire area between the Ramp Road and the moraine (see Fig. 2) was forced to drain into the channel running beneath the bridge. In addition, the thaw season of 1957 was abnormally warm (see paragraph 12). The peak flow in the channel beneath the bridge was estimated to be 500 cfs of meltwater.

The bridge supported all loads imposed upon it with no apparent strain. In July 1957, due to differential movement of the bents, the cable side-bracing slackened to the point of being useless. It was repaired and wooden-plank bracing was added. Otherwise no maintenance was required.

The bridge was completely supported on the ice and it moved with the ice. The amount of movement was measured by triangulation (see Appendix B, Table B-V). The entire bridge moved in a northerly direction (downhill) approximately 2.5 ft in 1 year. No detrimental effect on the bridge was apparent as a result of this movement, nor was there any significant differential movement with depth as the piles remained reasonably vertical.

Summary

47. In the summer of 1956, an 80-ft-long wooden-pile-bent bridge was constructed on the ice by six men in 2-1/2 weeks; they performed the work with a minimum of equipment and in inclement weather.

The bridge supported the heaviest mobile equipment at the site (29 tons) and performed satisfactorily for 1-1/2 thaw seasons with a minimum of maintenance.

During the unusually warm summer of 1957 failure of road culverts diverted large quantities of meltwater into the bridge channel, causing excessive meltwater flow beneath the bridge. Much erosion of the channel resulted, endangering the stability of the pile bents.

IX. CONCLUSIONS

Organization and equipment

48. In the TUTO area of northern Greenland, the short work season and limited number of days with good weather require that: (a) plans and schedules be carefully prepared in considerable detail, (b) personnel be specially selected for their technical ability and skills in all phases of the work, (c) close cooperation exist between civilian and military personnel and agencies, and (d) working hours be as long as possible commensurate with physical limits.

Twenty-two men operating nine 10-cu-yd dump trucks, one 2-cu-yd power shovel, one 3/4-cu-yd power shovel, six D8 bulldozers, and one motor grader can place approximately 890 cu yd of coarse gravel, or construct 300 ft of gravel road 2-1/2 ft deep and 30 ft wide, in 9-1/2 hours when the haul distance is 3 to 4 miles.

Work slowdown in constructing gravel roads in remote arctic areas can be decreased by providing spare equipment for use during breakdown of regular equipment. Ample spare parts should also be provided.

* Early in the 1958 thaw season the piles were undercut and the bridge abandoned.

A crawler-mounted, ladder-type ditching machine will cut trenches in ice efficiently, but the standard model needs modification to improve its maneuverability on rough ice surfaces.

A 5-ft-diameter hole can be drilled in ice to a depth of at least 70 ft with a helical auger and a suitable drill rig.

Weather

49. The measurement of all meteorological properties in an arctic area such as TUTO requires much intricate and carefully chosen equipment, and skilled technicians with experience in arctic operations. The U. S. Army Signal Corps, Meteorological Branch, has the necessary experience and capability for this type of operation.

The weather of the 1956 thaw season was normal, according to available records, except that an unusually deep snow cover was present at the start of the season.

The 1957 thaw season was unusual and possibly unique in that the air thawing index was 50% higher than any previously recorded, precipitation (rain) was approximately 2.5 in., and wind velocities were greater than those of other years of record (one storm had gusts greater than 90 mph).

The thaw season at Camp TUTO is about 72 days long; it starts about 13 June and ends about 22 August, but a 2-week variation in length and in start or finish date can be expected.

In a cool thaw season, the snow 3 miles out on the ice cap does not completely melt, as that area is close to the line dividing accumulation from ablation. In a warm thaw season, the 3-mile point is well within the ablation zone and as much as 2 ft of ice may melt. These extremes may occur in consecutive years.

As many as 10 workdays may be lost on road construction in one thaw season due to inclement weather, and as many as 20 days may be unsuitable for surveying or similar activities.

Snow cover on the ground is extremely variable because of wind and resultant drifting. Snow cover on the ice ramp, although not evenly distributed in depth, recurs in the same depth pattern from year to year. The range of depth is from 6 to 7 ft at the base of the ramp, from 1 to 2 ft at elevation 1800 to 2000 ft, and from 3 to 4 ft at elevation 2200 to 2500 ft.

Physiography and soils of the TUTO area

50. The active soil zone in the TUTO area averages about 38 in. in depth and is composed of silty sand (SM) with a dry density of 122 lb per cu ft and a water content of 10%. Not included in this description are the cobbles and boulders in the peripheries of the frost patterns which prevail over most of the area.

The permanently frozen overburden in the TUTO area extends to at least the maximum drilled depth, 62.3 ft. As disclosed by the borings, the first 7 ft below the permafrost table is typically a silty sand (SP or SM) with layers of silt (ML); this layer has a moisture content of from 20 to 100% and dry densities of from 45 to 110 lb per cu ft. The soil below the top 7 ft is typically a silty sandy gravel (GP, GM, or combination) with an occasional layer of silty sand (SM) and frequent boulders; moisture content varies between 3 and 13% and dry density between 128 and 145 lb per cu ft. Lacustrine deposits also occur having alternate varves of silt, sand, and ice, and occasional thin layers of clay.

The mean annual surface temperature of the undisturbed ground at TUTO is approximately 10 F.

The shallow depth of thaw in the TUTO area makes it necessary to bulldoze borrow materials into stockpiles before loading on dump trucks. However, an adequate amount of suitable borrow materials can be obtained in this manner within reasonable haul distances.

A coarse, highly permeable borrow material is available in considerable quantity in the form of clean boulders and cobbles (50% by weight of boulder sizes). The material can be found where there has been a washing of the surface soils by meltwater flow.

A silty gravelly sand is available for the surfacing of roads. The material provides a good surface from a trafficability standpoint, and wearing qualities are also acceptable. Although the percentage of fines is such that the soil is somewhat frost-susceptible and liable to frost heave and thaw weakening when moisture is available, the susceptibility is reduced substantially by the dryness of the climate and the consequent lack of available water under conditions of satisfactory drainage.

Most of the available borrow material is as described above; when it is stockpiled and mixed with the boulders and cobbles it contains about 4% (by weight) silt and 25% cobbles and boulders. This material is useful for constructing road embankments in ice-free areas, and for constructing dikes, berms, and miscellaneous fills on the ice.

There is a plentiful supply of boulders which can be crushed and used for surfacing roads that may be subjected to moderately heavy traffic.

Steam thawing of the surface soils at TUTO (by passing steam through pipes inserted in the frozen ground) is an impractical and uneconomical method of obtaining useful borrow soils. An excessive amount of heat energy is required, and the melting of ice in the soil together with the injection of steam creates excessive amounts of water. Extensive drainage and drying would be necessary to produce a useful borrow material.

Ice ramp

51. The smooth surface and gentle (4 to 7%) slope of the TUTO Ramp is apparently a unique condition for the edge of glacier ice, especially for the edge of the Greenland Ice Cap.

Measurements of surface movement of ice, by precise triangulation of permanent points in the road fill, show the ice to be essentially stagnant for the first 2000 ft. Beyond this point, the ice moves downslope: the horizontal component a maximum of 11 ft per year, the vertical component upward a maximum of 3 ft per year at about 3200 ft from edge of ice, zero at 6000 ft from the edge, and downward at a rate of about 1.5 ft per year beyond 6000 ft from the edge.

The Wilson inclinometer is a useful and satisfactory instrument for measuring subsurface ice movement.

At a point 1800 ft from the edge of the TUTO ice ramp the ice is 190 ft thick, and is underlain by moraine material (silty sandy gravel with boulders) to a depth of at least 48 ft.

There is no differential subsurface movement in the stagnant ice of the first 2000 ft of the ice ramp. Where the ice surface is moving horizontally between 9 and 11 ft per year and vertically between 1 and 2 ft per year, there is only slight differential movement of the top 200 ft of ice. However, in the area where the rate of vertical uplift of the moving ice is greatest as a result of overriding the stagnant ice, there is a differential movement in the top 200 ft, both horizontally and vertically, amounting to 17.5% decrease in the horizontal movement from the 50- to 200-ft depth and 100% decrease in the vertical movement in the top 200 ft. Additional years of record are required to confirm these values.

Piles inserted into the ice to depths less than 50 ft will not tilt significantly because there is little or no differential horizontal movement of the ice in the top 50 ft.

The natural crack pattern on the surface of the glacier ice is an indication of the direction and velocity of ice movement. Where movement is primarily horizontal, cracks were approximately evenly spaced and slightly oblique to direction of thrust. Where movement is strongly upward, cracks are closely spaced and in a checkerboard pattern, perpendicular and parallel to direction of thrust.

There is a net loss of ice due to ablation on the ice ramp, extending in unusually warm seasons as far as 3 miles out on the ice cap. In the first 3/4 mile of the ramp, as much as 11 ft of ice may be melted from the surface in a single thaw season. At a given ramp elevation the amount of ice melt varies from place to place, depending on the amount of winter snow cover and the concentration of dirt on the ice. The edge of the ice cap may recede more than 41 ft in a thaw season.

A gravel-fill road of sufficient thickness to prevent or nearly prevent ice melt beneath the roadbed may become perched above the ice surface as much as 11 ft in one season.

The net effect of ablation and movement on the ice ramp is a continuous recession of the edge of ice, a steepening of the slope of the first 3/4 mile, and the development of a steadily increasing hump in the road at the point where upward ice movement is greatest.

The volume and velocity of meltwater are so great that special consideration must be given to the prevention of erosion of road fills, culvert installations, etc. Maximum flow was observed to occur in 1957 during the first 2 weeks of July and daily at approximately 2:00 p.m.

Thaw of soils and melt of ice

52. The experimental procedure used to measure depth of thaw, i.e. of inserting plastic tubes filled with saturated sand in the ground and periodically observing the depth of thawed sand, is not a convenient and practical method for measuring thaw progression. Further investigation to improve the procedure is recommended.

In the TUTO area, the measured depth of thaw in the undisturbed ground ranged from 2.9 ft in 1954 to an average of 3.6 ft in 1957.

In the TUTO area a total depth of 5 ft of gravelly, sandy soil with a dry density of about 132 lb per cu ft and a moisture content of 5% is required to completely protect ice in the subgrade from thawing. At TUTO, this total depth may include the depth of the active zone, as the soil in the active zone is similar to that specified.

The amount of thaw of the ground surface prior to the accumulation of air thawing degree-days indicates that the ratio of surface thawing index to air thawing index must be appreciably greater than 1.0.

At 1000 ft out on the ice cap, where the air thawing index is only slightly lower than at the edge of ice, about a 5-ft-thick gravel road fill is required to completely protect the ice subgrade from melting. At 7700 ft from edge of ice, where the air thawing index is less than half that at the edge of ice, a 3-ft-thick gravel fill is not sufficient to completely protect the underlying ice from melting during an unusually warm summer.

In the absence of surface temperature data, it is essential to the general use of the modified Berggren formula for the prediction of thaw depth in soils that a value for the ratio of surface thawing index to air thawing index (n) be available. The n ratio for gravel surfaces and the undisturbed

ground surface at TUTO was 1.4 and 2.1 in 1956 and 1957, respectively, depending on such factors as the average wind velocity for the thaw season, the average seasonal cloud cover, and the air thawing index.

For design purposes in the Camp TUTO area, the modified Berggren formula gives a good prediction of the depth of thaw required to protect a subgrade beneath a gravel fill from thawing. A surface thawing index of 900 degree-days, a mean annual temperature of +10 F, and a length of thaw season of 80 days should be used.

Based on computations using the accepted method for multilayered soils, 3 ft of gravel fill on the ice will: (a) allow 0.25 ft of ice to melt beneath the fill in the first 1/2 mile of the TUTO ice ramp, (b) allow 0.1 to 0.2 ft of ice to melt at about 1 mile up the ramp, and (c) completely prevent ice melt 3 miles out on the ice cap during an unusually warm summer, such as in 1957.

Road construction

53. A gravel-fill road on the ice at an angle to the direction of meltwater flow should have crossroad culverts or provisions for directing flow away from the road. Without such provisions, erosion from meltwater flow may cause such damage that extensive maintenance operations will be required and failure of the road may occur.

Gravel fill can be placed on compacted snow to form a stable road, but where summer thaw produces flowing meltwater, which will easily and quickly erode the compacted snow, this procedure is not as practical as removal of the snow before fill placement.

A gravel-fill road placed on an ice slope of about 24 degrees by keying the gravel fill into trenches in the ice did not slide.

Because of the conditions prevailing on the TUTO ice ramp a culvert made of half-round, 36-in.-diameter, corrugated metal pipe is ineffective under a gravel-fill road on ice; the most important reason is the small size of the culvert. A small bridge would be an effective method of providing an adequate water crossing.

Rough ice can be effectively leveled for the construction of roads or other facilities by blasting and clearing ice in successive layers.

A road fill on ice should consist of a heavy, highly permeable, coarse soil to withstand the eroding tendencies of flowing meltwater and to permit the water from melting snow and thawing soil to drain freely from the embankment. The clean cobbles and boulders available in the TUTO area are excellent for this purpose. The fine soil available for surfacing the roads is only acceptable in the absence of a better material. The percentage of silt and fine sand in the fine soil is so high that dust control is necessary, and there is a tendency for the surfacing material to penetrate the coarse underlying soil, blocking the voids. Frost heave is not a problem because the surfacing material is quite dry at the time of freeze-up.

A depth of road fill of 2-1/2 ft will provide a stable road throughout about 2-1/4 thaw seasons. However, there is evidence that a 2-1/2-ft fill was barely adequate, and that further observations and measurements are required to establish a proper design depth.

Snow deeper than 1 ft should be plowed from the area before placing gravel fill. Also, channels should be plowed in the snow cover to direct the meltwater flow away from the road construction area.

Perching of the gravel-fill road on an ice ridge due to upthrust and to ablation of the surrounding ice averaged 6.2 ft a year at the point of greatest elevation in the 3 miles of road. A 30-ft-wide road without protecting berms or blankets of soil on each side will not be usable for as long as 10 years. The present road from the ice cap's edge to about 6000 ft out on the ice cap will fail, due to sloughing of the shoulders and melting of the underlying ice ridge, within 10 years. Beyond that point the rate of ablation decreases with increasing elevation and the road could be maintained for at least 10 years.

Cracks in the gravel-fill road resulting from cracking of the underlying ice have no detrimental effect on the road.

It is important that dust from the gravel road be controlled to prevent it from spreading over the ice surface and causing accelerated melting, and to prevent the loss of fines from the road surfacing. An effective and practical dust palliative is arctic diesel oil, spread at the rate of 0.3 gal per sq yd.

A 1-ft blanket or berm of gravel can reduce the melt of the ice surface to less than 5% of that of the uncovered ice. A gravel berm will reduce the rate of road perching (relative to the berm) to less than one-twentieth of that of a road not so protected. Recommended berm widths to provide protection of the road fill for 10 years are as follows:

First 1/4 mile of road	30 ft
Next 1/4 mile to 1-1/2 miles	20 ft
Next 1-1/2 miles to 3 miles	15 ft

Material used for constructing berms should contain sufficient coarse sizes to prevent undue washing by flowing meltwater, while retaining sufficient fines to provide insulating qualities. Crushed rock does not meet these criteria.

A road constructed of 6 in. of crushed rock placed directly on the ice becomes saturated with water from melt of the underlying ice. Three months of normal traffic at TUTO will cause excessive rutting and wear of such a road. A 12-in.-thick fill of crushed rock also develops soft areas from excessive meltwater, and 3 months of traffic will reduce the surface to a rough, though passable, condition. It is tentatively concluded that thin fills of crushed rock are not suitable for road construction on ice where melt of the ice surface occurs. Observations and tests are required for one more complete thaw season to confirm this conclusion.

Bridge

54. Under the conditions encountered on the ramp, it is feasible to construct a simple bridge, of the military expedient type, on the glacier ice when a crossing for heavy vehicles over rough ice or large meltwater streams must be provided.

Wooden pile bents can be used to support bridging of any desired type. The wooden piles can be placed in holes drilled in the ice and frozen in, using a backfill of water and ice. A bent consisting of three 12-in.-diameter wooden piles set in cold glacier ice will support a live load of at least 29 tons without detrimental deflection.

There is need for a simple, convenient augering device that can drill 18-in.-diameter holes at least 25 ft deep in ice. The machine should be easily portable, or self-propelled and able to maneuver on rough ice surfaces.

The life of the bridge under conditions such as those existing on the ramp will depend on the length of the span and the rate of erosion of the channel. The latter is controlled primarily by the quantity and velocity of water flow.

X. RECOMMENDATIONS

55. It is recommended that certain phases of the investigations be continued to further develop methods, techniques, and design criteria for construction of roads on ice and frozen ground. The following specific proposals are made:

The program of meteorological measurements should be continued in the same detail as in 1957; it should be continuous throughout the entire thaw season, or from about 1 May to 1 October.

Observations and measurements, as appropriate, should be continued to determine: cracking, heaving, and deformation of roads; performance of roads under traffic; ice melt under roads; performance of berms; and effect of meltwater flow on culverts, roads, and bridges. Special observations, including conducting an appropriate traffic test, should be made of the thin-fill test section constructed in 1957. Measurements of ice movement, both surface and subsurface, should be continued with at least the same detail and accuracy used in 1957.

A pilot study should be made of the rate and quantity of meltwater flow over a selected representative area of the ice ramp; the flow should be related to time of day, portion of the thaw season, and weather. Values should be determined which will aid in establishing criteria for the design of culverts, ditches, bridges, and similar structures.

Study of suitable designs for culverts and bridges should be continued by the construction of prototype structures.

Measurements should be continued of: rate and depth of thaw penetration in the undisturbed ground and in road fills on the ground and on the ice; subsurface temperatures in the ground and in the ice; and the rate and amount of ablation of the ice.

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APPENDIX A: PLANS OF TESTS, 1956 AND 1957

I. PLAN OF TEST, 1956

Objective

1. The overall objective of Project 1 in 1956 will be to continue the study of the feasibility of constructing gravel-fill roads on ice and snow surfaces encountered on the Greenland Ice Cap, with the investigations to be conducted in the area near TUTO, Thule Air Force Base, Greenland. The specific objectives of the project in the summer of 1956 will be: (a) to continue construction of roads started in 1954 and 1955, and (b) to continue investigations related to the road construction, leading to development of design and construction criteria.

Preliminary surveys and observations

2. During the winter of 1955-1956, First Engineer Arctic Task Force personnel will, at intervals as feasible, read the thermocouples that were installed in the summers of 1954 and 1955. Commencing 1 March 1956, the Task Force will take readings once every two weeks until the summer program is started, approximately in June.

A preliminary survey and reconnaissance of the condition of the roads in the TUTO area will be made approximately the first week in May 1956. Observations and measurements of the snow conditions and drifting will be made, and photographs of the most important features will be obtained.

1956 construction program

3. In planning a program of investigations in the TUTO area for the summer of 1956, two aspects have been considered: (a) the maintenance, improvement, and preservation of existing roads; and (b) new investigations and installations, including the construction of new road test sections. In practically all cases, the activities that will maintain, improve, and preserve the existing roads and build new sections of road for research purposes will also serve local operational needs.

Maintenance, improvement, and preservation of existing roads. From both the operational and investigational standpoints, the measures proposed under this heading are considered to be very important. The existing main ice ramp road is at present heavily depended upon to provide access to the upper portion of the ramp for vehicles. The following measures will be undertaken:

> **Stations 0+00 to 30+00.** This portion of the existing road has gone through two thaw seasons and has been subjected to summer thawing temperatures more intense than those on any other part of the road. It is doubtful that the shoulders of this road will remain stable through another thaw season. With modification to the design, however, it is considered the road may be maintained for several years. In the 1956 construction season, berms of 50-ft minimum width and necessary training dikes will be constructed on each side of the present road. Also, several sections of the berms will be tapered, with decreasing thickness from the road to the edge of the berm, to observe the differential melting of the ice due to berm thickness.
>
> **Stations 30+00 to 76+00.** This section of road was almost entirely reconstructed in 1955, and training dikes and berms were installed for experimental purposes. Results of the use of berms and dikes were favorable. This entire section of road could be furnished with berms and meltwater-control dikes, their exact location and design to be determined after

study of the observations made in 1955 and in the field during construction. It is contemplated that 50-ft-wide berms will be installed, with several tapered sections, and that training dikes will be extended some distance beyond the road to assure that no heavy meltwater streams will develop in the vicinity of the road.

Stations 76+00 to 98+00. This section of road is not subjected to as intense thawing conditions as is the lower section of the road, and the need for protection against excessive thawing is not as critical. A few dikes for diversion of surface flow were constructed in 1955, and the development of melt will be observed closely in the next year to determine the performance of the existing dikes and the possible need for more dikes and berms.

Transverse Road, Stations 0+00 to 8+00. If it is to be used for other than experimental purposes, that is, used as an access road to the ice tunnel, the transverse road will be widened from the present 24-ft width to a 30-ft width. Berms 50 ft wide will be added adjacent to the roadway; several berm sections will be tapered. The existing culverts will probably no longer function, because of their perched position, and will be abandoned.

Dust control. Since dust accumulation on the ice ramp causes an increase in the melt rate, dust palliatives will be added to the surface of the ice ramp roads.

New construction

Materials. For new construction, only coarse, free-draining materials will be used.

Extension of the main road. This section of road completed in 1955 has reached an elevation on the ice ramp at which the melting of the ice surface during the summer is distinctly less than it is at the lower end of the road. However, the road has still not reached the zone on the ice cap where the net yearly accumulation of ice or snow begins to become appreciable. It is presently considered that the optimum location for construction of gravel-fill roads on ice and snow is near the firn line. There the road will not become progressively buried under annual accumulations, and the thawing of the ice adjacent to the road will be a minimum.

Accordingly, the main road will be extended approximately 1-1/2 miles, to just above the firn line, and a load transfer area will be constructed at the terminus. The necessity for protective berms and lateral dikes may not be present at the higher elevations, but this can only be determined in the field from observations of road performance during the thaw season. The design of the road will follow that used in 1955, unless results of observations on test sections built in 1955 show a necessity to modify it. The road will have a standard cross section with a 30-ft-wide traveled way. The fill, exclusive of berms, will be approximately 2 ft thick, but it may have to be varied to suit surface conditions. The lower 1-1/2 ft of fill will consist of coarse, free-draining, gravelly or bouldery material; the top dressing will consist of a few inches of crusher-run fine gravel or similar free-draining material. Drainage facilities should be provided if required.

One additional experimental test section, using about three fill thicknesses appropriate to the climatic conditions, will be included near the end of the extended road to provide an additional thaw condition for study.

In construction to date, it has been the practice to bulldoze aside the snow overlying the hard ice base before placing the gravel fill. In 1956, the fill will be placed directly on the existing snow surface where the snow depth does not exceed about 2 ft. This will save the substantial effort required for bulldozing this snow aside, and will also improve the drainage situation by eliminating the large banks of snow which affect the local drainage near the

road during the thawing season. It is also possible that at the higher elevations bulldozed banks of snow would not melt completely during the thawing season, in which case they would induce an undesirable snowdrifting situation during the winter.

At the start of the construction season, a few experimental sections will be constructed parallel to the road. Various thicknesses of crushed-rock fill, such as 6, 12, and 18 in., will be used for short sections to determine the minimum thickness of fill which can be effectively placed over the existing, still essentially dry, snow cover. These experimental sections will be trafficked and the minimum thickness of fill needed to carry military traffic will be determined. These experiments will provide information of value in case it is necessary to construct gravel roads over snow surfaces under emergency winter conditions.

Field reconnaissance will be made in 1956 to determine where the main road can be widened sufficiently for construction of an experimental small airstrip or where a separate gravel airstrip can be built. At the end of the 1956 season, recommendation should be made as to whether or not such an airstrip should be built and, if so, its specific location.

Road to ice tunnel. It is considered that the most feasible method of gaining satisfactory access to the ice tunnel is by extending the experimental transverse road constructed in 1955.

While considerable quantities of material, man-hours, and equipment-hours are involved, valuable experience would be gained in the construction of roads across a rougher terrain than has been encountered on the main ramp. Such a road would have a highly permeable boulder base, and its design will be similar to that used in the 1955 construction season. Depth of fill will be generally 3 ft, except as it may be necessary to increase this depth to accommodate surface conditions of snow depth, meltwater flow, or grade. Where meltwater channels cross the road, various types of drainage structures will be installed for test purposes; however, the basic type of culvert for smaller streams on ice will be a semicircular Armco arc section.

At least one short, pile-supported bridge will be constructed across one of the deeper thaw channels, with the floor structure designed to shade the piles from the sun so far as possible.

Further test sections and field experiments. When the results of the 1955 tests are analyzed, and as observations are being made in the 1956 season of the performance of the test sections, new methods will undoubtedly suggest themselves. Additional test sections to investigate these methods will be constructed. However, approval of any substantial field changes in the Plan of Test will be obtained before work is initiated.

Soil tests

4. Tests of soil properties will be carried out at periodic intervals, as necessary, including the following:

Water content and density measurements in undisturbed ground in connection with thaw penetration measurements. Tests will be made on both thawed and frozen soils.

Water content and density measurements in road and test lane fills in connection with thaw penetration studies and with bearing capacity (CBR) evaluations versus seasonal changes. Cone penetrometer tests will be conducted where applicable.

Identification and classification tests performed on all types of soils encountered, as applicable, including sieve, hydrometer, and Atterberg limits tests.

Snow and ice tests

5. In connection with placement of gravel fill directly on snow surfaces, tests will be performed to record the properties of the supporting material, including CBR, cone penetrometer, density, and grain size. These tests will cover the properties of the undisturbed snow and, at a later date, the properties of the disturbed snow.

Survey measurements

6. Survey activities will consist of the following:

Bench marks, base lines, etc., established as necessary, to maintain control of construction operations and to provide basis for as-built records of installation.

Periodic cross sections and profiles of roads and test installations obtained, as necessary, to record depths of snow, melting of ice surface, character of road surface, etc., including levels on reference plates set at base of gravel fill in test lanes. They will be observed at proper intervals of time and at distances to ±1000 ft or beyond any effect of dust.

Effects of ice movements on earth-fill roads placed on ice masses that undergo differential movement ascertained. These movements are determined by comparison of annual changes in elevation on selected cross sections. That is, if a given embankment station moves downslope several feet in a year, there will be a general change in elevation of the cross section; the general change must be distinguished from that caused by ablation of the surface in that section. The occurrence of lateral movements of the road should also be known; therefore, the necessary measurements will be made. While some progress has been made in 1955 toward obtaining these measurements, it has been found that an adequate investigation requires more equipment, manpower, and organization than has yet been applied. The following requirements are contemplated: (1) the assignment of a separate and fully equipped survey party to the task, and (2) the establishment of stable, permanent triangulacion stations and bench marks from which elevations and base lines can be obtained from year to year without introducing unknown errors due to movement of the reference points or stations.

Temperatures and allied data

7. Temperature and other weather data will be recorded regularly throughout the field season. Air temperatures will be measured by several recording thermographs, one located at the intersection of "P" Mountain Road and the TUTO Approach Road, one at TUTO Camp, and two or more on the ice cap. In cooperation with SIPRE, which is expected to have several parties located in the TUTO area, measurements will be made of wind speed and direction, relative humidity, barometric pressure, and air temperature.

Ground surface and subsurface temperatures will be measured at the thermocouple installations made in 1954 and 1955.

It has been known for some years that predictions of summer thaw penetration in earth fills and under pavements in far northern latitudes, such as the Thule Air Force Base area, may be in error as much as 200 to 300% if computations are based solely on air temperatures. Again, thaw is observed to start in the spring as much as a full month before the average daily air temperature rises to 32 F. The principal cause of this discrepancy is that current methods of predicting freeze and thaw do not take the radiation factor into account. In very high latitudes summer solar radiation

has an extremely important effect on depth of thaw penetration. Some measurements of the contribution of solar radiation in the TUTO area were made by Dr. Schytt and his group in 1954 in a SIPRE study. However, no instruments were available for such measurements in 1955, and no radiation data were obtained. Since it is very important to be able to make reasonably accurate predictions of summer thaw penetration in connection with construction in these far-north areas, a complete study of all the factors contributing to the freeze-thaw balance will be initiated in the TUTO area during 1956. Data will be obtained from both land and ice areas. This program will be developed in close co-operation with SIPRE.

Measurements of thaw penetration

8. The studies of the actual rates and characteristics of thaw penetration in various active zone materials in the TUTO area, commenced in 1954, will be continued to the extent indicated by analysis of the 1954 and 1955 results. While the principal measure of thaw penetrations will be subsurface thermocouple readings, occasional test pits and probings will be required to confirm and extend these measurements.

Drainage study data

9. Effectiveness of culverts, training dikes, and bridges will be recorded.

Data will be recorded on widths, depths, and slopes of principal streams and on velocities and quantities of flow.

Records will be kept of rates of erosion resulting from streamflow. These will include photographs.

Effect of dust

10. Analyses of the effect of dust on the ice surface, started in 1955, will be continued. Distribution of dust with distance from road center line will be recorded. Correlation of dust concentration with observed thaw degradation will be attempted.

Road performance observations

11. Observations of the traffic and general performance of all roads and test fills in the TUTO area will be continued in 1956.

In 1955 one helicopter reconnaissance of the NUNA Road was made. In 1956 surveys of the local roads will again be made, including not only the NUNA Road but also roads near Thule Air Force Base. These surveys should be made relatively early in the season, before appreciable summer maintenance can be accomplished and while roads are in their poorest condition because of relatively shallow depth of thaw.

Investigation of availability of borrow materials

12. Results of this phase of the investigations are considered to have a broader application than simply the procurement of materials for the construction of the ramp roads at TUTO. Conditions may arise in which construction must be carried out during seasons when borrow sources are completely frozen, or in which borrow sources are limited in area and it is necessary to consider excavation to substantial depth in permafrost; therefore, the 1956 program will include the following investigations:

Core borings. If deep excavations are necessary in a potential borrow source, it would be

essential to determine the type of soil present. In soils containing gravel, cobbles, and boulders, such as in the TUTO area, this is difficult if exploration is required beyond a depth of about 10 ft. Several core borings to a depth of 20 ft will be made with the objectives: (1) of determining most suitable methods of obtaining relatively undisturbed borings in coarse-grained soil deposits containing ice, or in soil foundations containing ice; (2) of determining what conditions would be encountered if the local TUTO borrow areas were to be worked to a substantial depth; (3) of providing correlation data for steam thawing experiments; and (4) of providing information of value in determining the local geological history.

The key requirement of such explorations would be the recovery of undisturbed cores in which the ice lenses are sufficiently intact to give an accurate evaluation of the amount of settlement and amount of water release which would occur on thawing. A requirement which is almost as important is that the drilling equipment be as lightweight and portable as possible so that it will be possible to fly such equipment in to remote sites. However, the first of these requirements is the one of immediate concern.

Test pit. If a core boring study as discussed above is not included in the 1956 program, it is recommended that at least one test pit be excavated to about 20 ft, in conjunction with the steam-thaw tests, for accurate evaluation of the soil and ice conditions present.

Steam thawing. Steam thawing experiments will be carried out in 1956 in accordance with the plans originally drafted for 1955.

Study of natural thawing in excavated areas. Examination will be made of the permafrost materials which have been exposed to summer thaw in past seasons by borrow excavations, both in the TUTO area and in the Thule Air Force Base area. Evaluations will be made of: (1) the time required for newly thawed materials to become sufficiently dry for use as fill, (2) pit drainage requirements, and (3) the rate of thaw penetration, with depth, in newly exposed permafrost.

Work output studies

13. An important part of the development of methods and techniques for the construction of roads in the TUTO area is the analysis of equipment and manpower needs for a particular job. In 1955 a careful record was kept of equipment performance, time requirements, manpower, etc. Such records will be repeated for all construction of this nature in 1956.

Consultants

14. Consultants may be required, and arrangements for their services will be made as the need arises.

II. PLAN OF TESTS, 1957*

Objective

15. The overall feasibility of constructing gravel-fill roads on glacial ice surfaces having now been established, the objectives of the 1957 program are to gather added evidence regarding methods, techniques, and criteria developed to date, and to obtain measurements defining the conditions under which these criteria are applicable, with a view toward determining the feasibility of their use in other climatic and surface conditions.

* Revised 12 March 1957.

Specifically, the project will include the following categories of investigations:

a. Observations of the performance of roads, bridges, etc., constructed to date.

b. The repeating and augmenting of measurements of meteorological factors, subsurface properties, freeze-thaw characteristics, and ice movement. Core drilling will be used in connection with these measurements.

c. Construction of a few test sections to complete the information needed to specify the requirements for berm construction and for the minimum depth of fill for roads on ice.

d. Cooperation in the layout and planning of approach roads in southern Greenland, as required.

Observations

16. Observations will be made of the performance of the facilities constructed to date. The observations will include visual surveys of slumping, heaving, and movement of the road fills and ablation or melting of the ice surface. Visual observations will be made and records kept of such items as the performance of roads and the bridge under traffic, the effectiveness of the culverts, the effect of meltwater flow, and the effectiveness of berms and dikes. A photographic record will also be kept.

Measurements

17. Requirements for meteorological measurements have been submitted to the U. S. Army Signal Corps. In general, the requirements submitted are similar to those for the 1956 program. Stations will be set up and operated by the U. S. Army Signal Corps at three locations as follows: (1) the edge of the ice cap, (2) one mile inland on the ice cap, and (3) three miles inland on the ice cap.

a. Project requirements for measurements at Stations 1 and 3 include the following:

(1) Temperatures at three levels above the ground surface (suggested levels 4, 8, and 16 ft), at the surface, and two levels below the surface (depth selected should be multiples of 2). The temperature-sensing elements will be protected from radiation and all temperatures will be continuously recorded.

(2) Wind velocities at three levels above the surface, continuously recorded. (The suggested levels are 4, 8, and 16 ft above the surface.)

(3) Total and net radiation continuously recorded.

(4) Sunshine duration continuously recorded at one site only. Instrumentation will be provided by ACFEL.

(5) Relative humidity continuously recorded.

(6) Wind velocity measured and continuously recorded at three levels (suggested levels 4, 8, and 16 ft).

(7) Barometric pressure continuously recorded.

(8) Six-hourly observations of maximum and minimum temperatures, wind direction, and relative humidity (psychrometer) obtained at one level above surface (suggested level, 4-1/2 ft above surface). Also a check of recording instruments will be made during these observation periods.

b. Project requirements at Station 2 include the following:

(1) Temperature and relative humidity continuously recorded.

(2) Continuous measurements of temperatures at road "surface" plus two levels below surface. Continuous measurement of temperature at one level in air above ice 200 yd from road, and at surface and two levels below surface, if possible. Continuous measurement of wind velocity at one level above ice surface.

(3) Continuous measurement of total hemispherical radiation and net radiation over ice, net radiation only over road.

(4) Six-hourly observations to also serve as a check on recording instruments.

c. Periodic readings of subsurface temperatures will be made at the thermocouple assemblies previously installed. In connection with these readings, measurements will be made of the rate of thaw penetration in the ground by means of the devices installed in 1956 for this purpose.

d. Periodic measurements of the lateral and vertical movement of the ice and road will be made using survey methods, including triangulating from the base line and permanent stations established in 1956, and cross sectioning, profiling, and leveling at representative locations along the ramp road. These measurements will include recording of any slumping, heaving, and movement of the road embankments and ablation of the ice and snow surfaces. Two or three installations will be made on the ice surface to continuously record movement between two points approximately 100 ft apart. Deep hole drilling will be performed in the ice at three locations along the road where ice movements are known to be appreciable and at approximately 25 shallow holes in various areas on the ice ramp. Attempts will be made to determine the characteristics of the ice as it may affect the life and performance of the road, including the presence of shear planes and the depth of bedrock, and subsurface movements will be obtained by means of an inclinometer lowered into the drill hole. SIPRE will determine the physical characteristics of the undisturbed ice cores. Patterns of surface ice cracks will be mapped and photographed several times during the season to determine if there is any correlation between surface cracking and ice movement.

e. Core drilling of the overburden and embankments in the vicinity of TUTO to depths of 10 to 20 ft will be undertaken to obtain complete and adequate data on the characteristics of the upper layer of the overburden in the frozen state, particularly with regard to moisture content and density. The work will be performed while the ground is still frozen. Approximately 25 holes are contemplated. At the same locations, the changes in moisture content in the active zone will be followed during the thaw season by means of test pits. SIPRE personnel will assist in locating drill hole locations so that these data can be used in conjunction with their patterned-ground study.

Construction of test sections

18. Construction of test sections will be as follows:

Experimental sections of berms to determine the optimum width for adequate road protection.

Berms will be constructed of random material approximately 1 ft thick. Each test section will be 500 ft long, and two sections will be constructed, one 10 ft wide and one 20 ft wide. Berms having widths of 30 and 50 ft have already been constructed, so four widths will be available for observations. Approximately 600 yd of borrow would be required to construct the two test berms, which would occupy the equipment and number of men used on the 1956 construction for about 3 working days.

Test sections to determine the minimum thickness of fill which can be effectively placed on the ice to provide a trafficable roadway for heavy wheeled vehicles. Two sections, one 6 in. thick and the other 12 in. thick, will be constructed parallel and adjacent to the present road so that traffic can be diverted to cover them. Crushed and screened rock or screened random gravel will be used for the fills. It is estimated that approximately 500 yd of material will be required and that construction will occupy about 3 working days.

APPENDIX B: INVESTIGATIONAL DATA

Table B-I. Project Personnel, 1956

Position	Affiliation	Date in Field
	Permanent Project Personnel	
Project Engineer (1)	ACFEL	6/10/56-9/2/56
Asst Project Engineer (1)	WES	6/4/56-9/1/56
Construction Supervisor (1)	WES	6/4/56-9/1/56
Geologist (1)	ACFEL	6/10/56-9/2/56
Soils Technician (1)	WES	6/4/56-9/1/56
Soils Technician (1)	EATF	6/1/56-9/15/56
Surveyor (Party Chief) (1)	ACFEL	6/10/56-9/1/56
Surveyor (Party Chief) (1)	ACFEL	6/14/56-9/1/56
Engineering Aide (1)	ACFEL	6/14/56-9/1/56
Surveyor (1)	EAFT	6/10/56-9/2/56
Rodman (2)	EATF	6/10/56-9/2/56
	Drill Crew	
Driller (1)	WES	6/5/56-7/10/56
Driller's Helper (1)	WES	6/5/56-7/10/56
Drill Crewman (2)	EATF	6/6/56-7/10/56
	Supervisors and Consultants	
Project Supervisor	H. W. Stevens, ACFEL	6/4/56-7/6/56
Inspection	K. A. Linell, Chief, ACFEL	9/6/56-9/11/56
General Consultant	Dr. Mikael J. Hvorslev, Consulting Engineer, WES	6/29/56-7/21/56
Consultant for Drilling Operations	T. B. Goode, Chief, Inspection and Exploration Section, Soils Division, WES	4/14/56-7/2/56
	Military Construction Personnel	
Construction Foreman (2)	EATF	6/1/56-9/5/56
Shovel Operator (3)	EATF	6/1/56-9/5/56
Bulldozer Operator (6)	EATF	6/1/56-9/5/56
Truck Driver (9)	EATF	6/1/56-9/5/56
Grader Operator (2)	EATF	6/1/56-9/5/56
Compressor Operator (1)*	EATF	6/1/56-9/1/56
Tank Car Heater Operator (1)*	EATF	6/1/56-9/1/56
Crusher Operator (2)*	EATF	6/1/56-9/1/56
Demolition Specialist (1)*	EATF	6/1/56-9/1/56

* Part time.

Table B-II. Equipment and Materials, 1956

Item	Supplier	Use
Bulldozer (D8) (6)	EATF	Road construction
Truck, dump, 10-cu-yd (9)	EATF	Road construction
Shovel, tractor-mounted		
2-cu-yd (1)	EATF	Road construction
3/4-cu-yd (1)	EATF	Road construction
Grader, road, motorized (1)	EATF	Road construction
Scraper, towed-type, 12-cu-yd (1)	EATF	Road construction
Rock crusher, 25-cu-yd/hr (1)	EATF	Road construction
Truck, dump, 2-1/2-ton (1)	EATF	Transport drilling pipe, stems, bits, etc. Reaction for CBR tests
Compressor, truck-mounted, 210-cu-ft/min (1)	EATF	Provide air pressure for core drilling and operate wagon drill and other pneumatic tools
Heater, asphalt, 3-car (1)	EATF	Provide pressurized steam for steam-thaw tests
Crane, truck-mounted, 10-ton (1)	EATF	Place wood piles, timbers, Treadway bridge sections, etc.
Tractor, crawler-type (D8), with boom (1)	EATF	Hoist drill when drilling holes in ice for wooden piles
Jeep (2)	EATF	Transportation
Truck, 3/4-ton (1)	EATF	Transportation
Generator, 5 kw (1)	EATF	Used to operate drying ovens in soils laboratory
Distributor, water, truck-mounted (1)	EATF	Distribute water and diesel oil as dust palliative
Drill rig, truck-mounted, complete with core barrels, bits, rods, and all accessories (1)	WES	Extract frozen soil samples to depths of more than 50 ft
Survey set, complete (1)	EATF	Provide line and grade for road construction, cross sections, and location for as-built record, etc.
Theodolite, range poles (1)	WES	Precise triangulation
Ice-drilling equipment	ACFEL	Drill holes for wooden piles, instrumentation
Weather instrumentation; barograph; anemometers with recorders, sunshine duration; hygrothermographs, shelters, masts	ACFEL WES	Augment instrumentation furnished by USA Signal Corps to measure weather characteristics
Soil testing equipment	WES	Conduct tests for density, water content, grain size, plasticity, and CBR
Devices to measure depth of thaw	ACFEL	Investigate new methods of measuring thaw depths
Equipment to conduct steam-thaw tests--pipe, steam hose, nozzles, fittings	ACFEL	Conduct tests of methods of thawing frozen soil
Camera, film, light meters, etc.	ACFEL	Provide photographic record of investigations
Portable potentiometers, accessories	ACFEL	Read temperatures from thermocouple installations
Pipe, caps, oil, wax	ACFEL	Construct permanent bench mark
Wooden piles, timbers, bolts	ACFEL	Construct bridge
Thermocouple wire, panels, plastic tubing, pipe	ACFEL	Installations for subsurface temperature measurements
Office supplies, drafting supplies, survey notebooks, etc.	ACFEL	Records, plotting, computing

Table B-III. Project Personnel, 1957

Position	Affiliation	Date in Field
	Permanent Project Personnel	
Project Engineer (1)	ACFEL	6/6/57-8/29/57
Asst Project Engineer (1)	WES	4/26/57-8/29/57
Geologist (1)	ACFEL	4/26/57-7/27/57
Soils Technician (1)	WES	5/2/57-7/21/57
Engineering Aide (1)	ACFEL	6/14/57-8/29/57
Engineering Aide (1)	EATF	4/11/57-8/29/57
Survey Party (Chief) (2)	ACFEL	6/6/57-8/29/57
Rodman (1)	EATF	6/10/57-8/29/57
Rodman (1)	EATF	5/15/57-8/29/57
Rodman (1)	EATF	6/28/57-8/29/57
	Drill Crew	
Driller (1)	WES	4/26/57-7/2/57
Driller's Helper (1)	WES	5/2/57-7/7/57
Drill Crewman (1)	EATF	5/20/57-6/15/57
Drill Crewman (1)	EATF	5/14/57-7/1/57
	Supervisors and Consultants	
Project Supervisor	H. W. Stevens, ACFEL	4/26/57-6/11/57
Inspection	C. R. Foster, formerly Chief, Flexible Pavement Branch, WES	6/12/57-6/14/57
Inspection	S. J. Knight, Chief, Army Mobility Research Branch, WES	6/12/57-6/14/57
General Consultant	Dr. Mikael J. Hvorslev, Consulting Engineer, WES	5/11/57-5/25/57
Consultant for Inclinometer	S. D. Wilson, A/E	5/11/57-5/25/57
Consultant for Drilling Operations	T. B. Goode, Chief, Inspection and Exploration Section, Soils Division, WES	5/11/57-5/26/57
	Military Construction Personnel	
Construction Foreman (1)	EATF	6/24/57-7/6/57
Shovel Operator (3)	EATF	6/24/57-7/6/57
Bulldozer Operator (4)	EATF	6/24/57-7/6/57
Truck Driver (6)	EATF	6/24/57-7/6/57
Grader Operator (3)	EATF	6/24/57-7/6/57

Table B-IV. Equipment and Materials, 1957

Item	Supplier	Use
Bulldozer (D8) (3)	EATF	Construct test berms and test roads
Truck, dump, 10-cu-yd (5)	EATF	Construct test berms and test roads
Shovel, tractor-mounted		
2-cu-yd (1)	EATF	Construct test berms and test roads
3/4-cu-yd (1)	EATF	Construct test berms and test roads
Grader, road, motorized (1)	EATF	Construct test berms and test roads
Rock crusher, 25-cu-yd/hr (1)	EATF	Construct test berms and test roads
Distributor, water, trailer-mounted (1)	EATF	Distribute water and diesel oil as dust palliative
Truck, dump, 2-1/2-ton (1)*	EATF	Transport drilling pipe, stems, bits, etc.
Compressor, truck-mounted, 210-cu-ft/min (1)*	EATF	Provide air pressure for drilling and to operate pneumatic tools
Tank, trailer-mounted, 500-gal (1)*	EATF	Provide water for drilling operations
Jeep (2)	EATF	Transportation
Truck, 3/4-ton (1)	EATF	Transportation
Immersion heater (5)	EATF	Used to heat antifreeze for inclinometer tube installations
Drum, 55-gal (5)	EATF	Used to heat antifreeze for inclinometer tube installations
Generator, 5 kw (1)**	EATF	Used to operate drying oven in soils laboratory
Survey set, complete (1)	EATF	Provide record of cross sections and profiles, and layout for test roads
Wannigan (1)	EATF	Weather shelter near drilling site
Hand coring and noncoring augers	ACFEL	Drilling operations in ice
Ice and soil density test apparatus	ACFEL	Test for density of ice and frozen soil
Thermocouple wire, panels, plastic tubing, pipe	ACFEL	Installations for subsurface temperature measurement
Portable potentiometers and accessories	ACFEL	Read temperatures from thermocouple installations
Drill rig, truck-mounted, complete with core barrels, bits, rods, and all accessories	WES	Drill holes in ice for inclinometer tubes. Extract cores of ice to depths of 200 ft. Also for core drilling in frozen soils
Soil test equipment	WES	Conduct tests for density, water content, grain size, plasticity, and CBR
Theodolite, self-leveling level (1)	WES	Precise triangulation and levels
Arctic clothing	WES	Provide protection from arctic weather
Tubing, plastic, 900-ft	WES	Installation in ice to provide guide for inclinometer
Office supplies, manuals, survey notebooks, etc.	ACFEL	Records, plotting, computing, etc.
Cameras, film, light meters, etc.	ACFEL	Provide photographic record of investigations
Approximately 500 gal glycerin-base antifreeze	EATF	Used in drilling and installing plastic inclinometer tubes
Approximately 4000 gal arctic diesel oil	EATF	Drilling fluid

* Part time.

** Later changed to 3 kw.

Table B-V. Ice Movement Measurements

Point	Period	Horizontal		Vertical	
		Ft	Direction	Ft	Direction
		Ramp Road			
MP-1	7 July 1956-7 Aug 1956	0.02	N63°25'W	0.03*	Down
	7 Aug 1956-21 Aug 1956	0.14	N30°10'W	0.01*	Down
	21 Aug 1956-13 June 1957	0.12	S65°35'W	0.12	Down
	13 June 1957-10 July 1957	0.18	S19°25'W	0.06	Down
	10 July 1957-8 Aug 1957	0.19	N18°25'E	0.23	Down
	8 Aug 1957-22 Aug 1957	0.12	South	0.06	Down
MP-17	8 July 1957-8 Aug 1957	0.93	N66°30'W	0.17	Down
	8 Aug 1957-22 Aug 1957	0.21	S73°20'W	0.25	Down
MP-66	7 July 1956-7 Aug 1956	0.56	N53°45'W	0.28	Up
	7 Aug 1956-20 Aug 1956	0.42	N75°00'W	0.08*	Up
	20 Aug 1956-13 June 1957	5.38	N70°05'W	2.66	Up
	13 June 1957-10 July 1957	0.67	N80°15'W	0.24	Up
MP-67	8 Aug 1957-19 Aug 1957	0.54	S83°40'W	0.03	Down
MP-8	7 July 1956-7 Aug 1956	0.63	N66°40'W	0.26*	Up
	7 Aug 1956-20 Aug 1956	0.51	N64°25'W	0.06*	Up
	20 Aug 1956-28 June 1957	6.68	N72°15'W	1.75	Up
	28 June 1957-9 July 1957	1.19	N84°10'W	0.11*	Up
	9 July 1957-8 Aug 1957	0.36	N28°00'W	0.14*	Up
	8 Aug 1957-21 Aug 1957	0.63	N88°10'W	0.02	Down
MP-10	24 July 1956-7 Aug 1956	0.29	N80°15'W	0.04*	Up
	7 Aug 1956-20 Aug 1956	0.58	N81°00'W	0.13	Down
	20 Aug 1956-28 June 1957	8.99	N75°00'W	0.80	Up
	28 June 1957-9 July 1957	1.00	N78°30'W	0.06*	Up
	9 July 1957-8 Aug 1957	0.59	N46°20'W	0.09*	Up
	8 Aug 1957-21 Aug 1957	0.72	N88°25'W	0.05	Down
MP-16	15 June 1957-8 July 1957	1.15	N85°00'W	0.16*	Down
	8 July 1957-8 Aug 1957	0.93	N45°00'W	0.12*	Down
	8 Aug 1957-20 Aug 1957	0.47	S77°45'W	0.11*	Down
MP-14	28 Aug 1956-28 June 1957	10.05	N85°50'W	1.14*	Down
	28 June 1957-29 July 1957	1.06	N62°30'W	0.14*	Down
	29 July 1957-20 Aug 1957	0.56	S19°45'W	0.17	Down
MP-15	20 Aug 1956-28 June 1957	8.50	S77°10'W	1.20	Down
	28 June 1957-24 July 1957	0.55	N56°00'W	0.31	Up
	24 July 1957-20 Aug 1957	0.97	S15°30'E	0.16	Down
		Transverse Road			
MP-7	7 July 1956-7 Aug 1956	0.18	N16°25'W	0.20	Up
	7 Aug 1956-21 Aug 1956	0.21	S76°00'W	0.02*	Up
	21 Aug 1956-15 June 1957	1.51	N61°05'W	0.47	Up
	15 June 1957-10 July 1957	0.26	N62°30'W	0.00	None
	10 July 1957-9 Aug 1957	0.03	West	0.16	Up
	9 Aug 1957-21 Aug 1957	0.08	N82°50'W	0.05	Down
MP-11	24 July 1956-7 Aug 1956	0.02	N26°35'W	0.14	Up
	7 Aug 1956-21 Aug 1956	0.09	N6°20'E	0.00	None
	21 Aug 1956-15 June 1957	0.84	N60°05'W	0.10	Up
	15 June 1957-10 July 1957	0.27	N49°10'W	0.00	None
	10 July 1957-9 Aug 1957	0.10	S16°40'E	0.01	Down
	9 Aug 1957-21 Aug 1957	0.09	S12°30'E	0.26	Down
		(Continued)			

Note: Location of points shown in Figure 2.
MP, movement pin in road fill.
B, bridge bent.
NM, not measured.
D, tube in drill hole.

* Interpolated between actual measurements.

Table B-V (Continued)

Point	Period	Horizontal Ft	Horizontal Direction	Vertical Ft	Vertical Direction
Transverse Road (Continued)					
MP-13	27 July 1956-7 Aug 1956	0.05	S 68°10'W	0.01*	Up
	7 Aug 1956-20 Aug 1956	0.13	N38°40'W	0.01*	Up
	20 Aug 1956-15 June 1957	0.90	N44°40'W	0.03*	Up
	15 June 1957-10 July 1957	0.18	S 66°20'W	0.07*	Up
	10 July 1957-9 Aug 1957	0.07	N26°35'E	0.11*	Up
	9 Aug 1957-22 Aug 1957	0.10	S 24°00'E	0.02	Up
MP-18	6 July 1957-29 July 1957	0.28	N70°55'W	0.36	Down
	29 July 1957-22 Aug 1957	0.26	N17°45'W	0.28	Down
Bridge Bents					
B-1	28 Aug 1956-6 July 1957	1.85	N66°20'W	NM	
	6 July 1957-29 July 1957	0.29	N80°15'W	NM	
	29 July 1957-22 Aug 1957	0.16	S 75°05'W	NM	
B-2	28 Aug 1956-6 July 1957	2.10	N64°05'W	NM	
	6 July 1957-29 July 1957	0.27	N77°00'W	NM	
	29 July 1957-22 Aug 1957	0.24	N22°15'W	NM	
B-3	28 Aug 1956-6 July 1957	2.16	N60°15'W	NM	
	6 July 1957-29 July 1957	0.39	N73°25'W	NM	
	29 July 1957-22 Aug 1957	0.15	N27°10'E	NM	
B-4	28 Aug 1956-6 July 1957	2.09	N57°30'W	NM	
	6 July 1957-29 July 1957	0.31	N60°55'W	NM	
	29 July 1957-22 Aug 1957	0.15	N11°20'E	NM	
B-5	6 July 1957-29 July 1957	0.29	N71°35'W	NM	
	29 July 1957-22 Aug 1957	0.22	N7°45'E	NM	
Drill Hole Tubes					
D-11	13 June 1957-8 July 1957	0.25	N73°45'W	NM	
	8 July 1957-8 Aug 1957	0.27	N61°30'W	NM	
	8 Aug 1957-19 Aug 1957	0.61	S 19°00'W	NM	
D-10C	3 July 1957-8 Aug 1957	0.27	N41°00'W	NM	
	8 Aug 1957-21 Aug 1957	0.37	S 60°40'W	NM	
D-10	13 June 1957-8 July 1957	0.79	N87°05'W	NM	
	8 July 1957-8 Aug 1957	0.39	N82°30'W	NM	
	8 Aug 1957-19 Aug 1957	0.68	S 54°00'W	NM	
D-10D	3 July 1957-8 Aug 1957	1.16	N72°30'W	NM	
	8 Aug 1957-21 Aug 1957	0.44	S 76°55'W	NM	
D-14	28 June 1957-9 July 1957	1.54	N50°00'W	NM	
	9 July 1957-8 Aug 1957	0.57	N60°45'W	NM	
	8 Aug 1957-21 Aug 1957	0.99	S 00°35'W	NM	
D-12	28 June 1957-9 July 1957	0.91	N86°00'W	NM	
	9 July 1957-8 Aug 1957	0.73	N48°50'W	NM	
	8 Aug 1957-20 Aug 1957	0.56	S 81°45'W	NM	
D-17	2 July 1957-29 July 1957	0.99	N73°35'W	NM	
	29 July 1957-19 Aug 1957	0.23	S 15°50'W	NM	
D-15A	6 July 1957-29 July 1957	0.18	N86°40'W	NM	
	29 July 1957-21 Aug 1957	0.30	N27°25'E	NM	

* Interpolated between actual measurements.

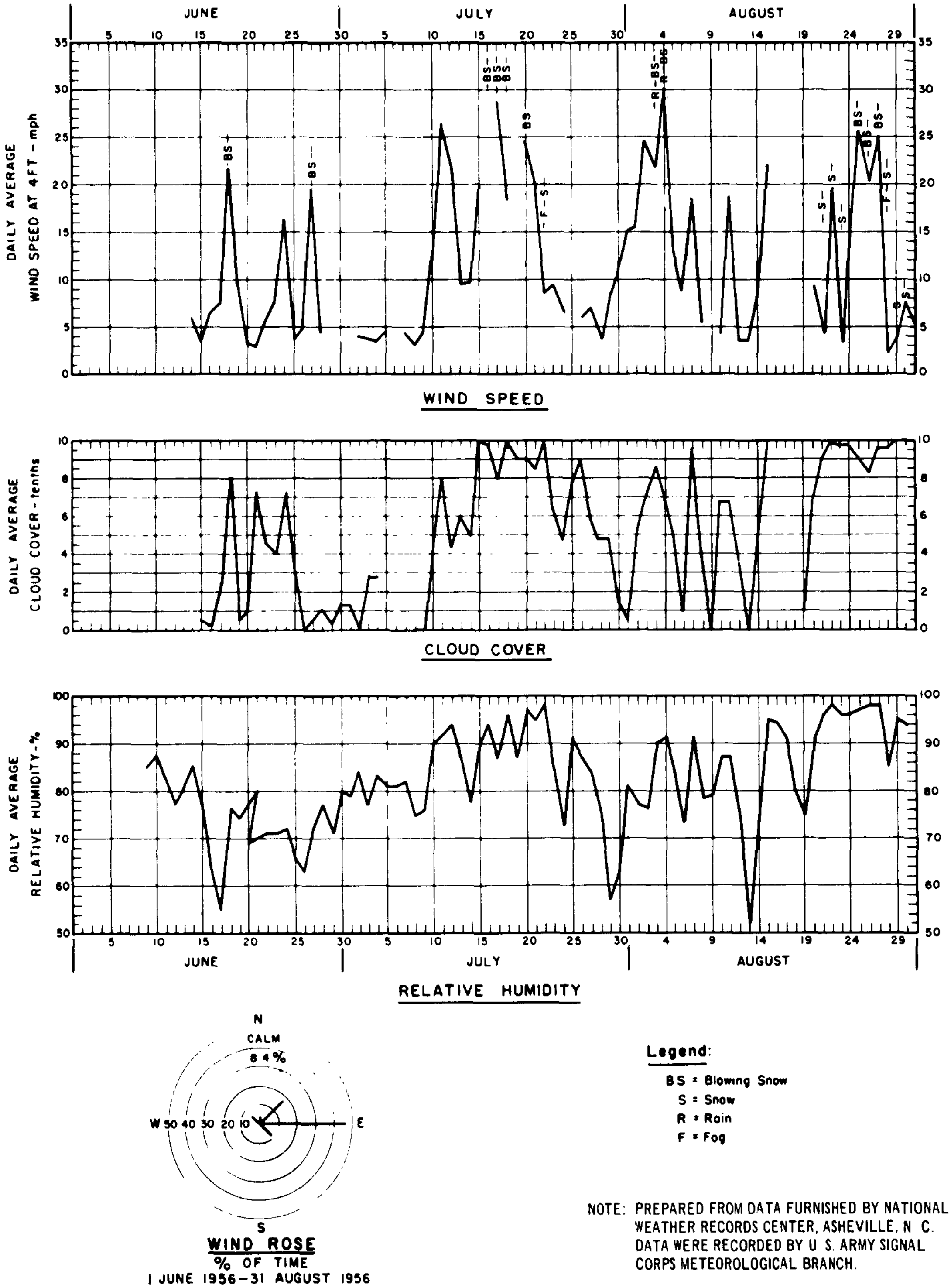
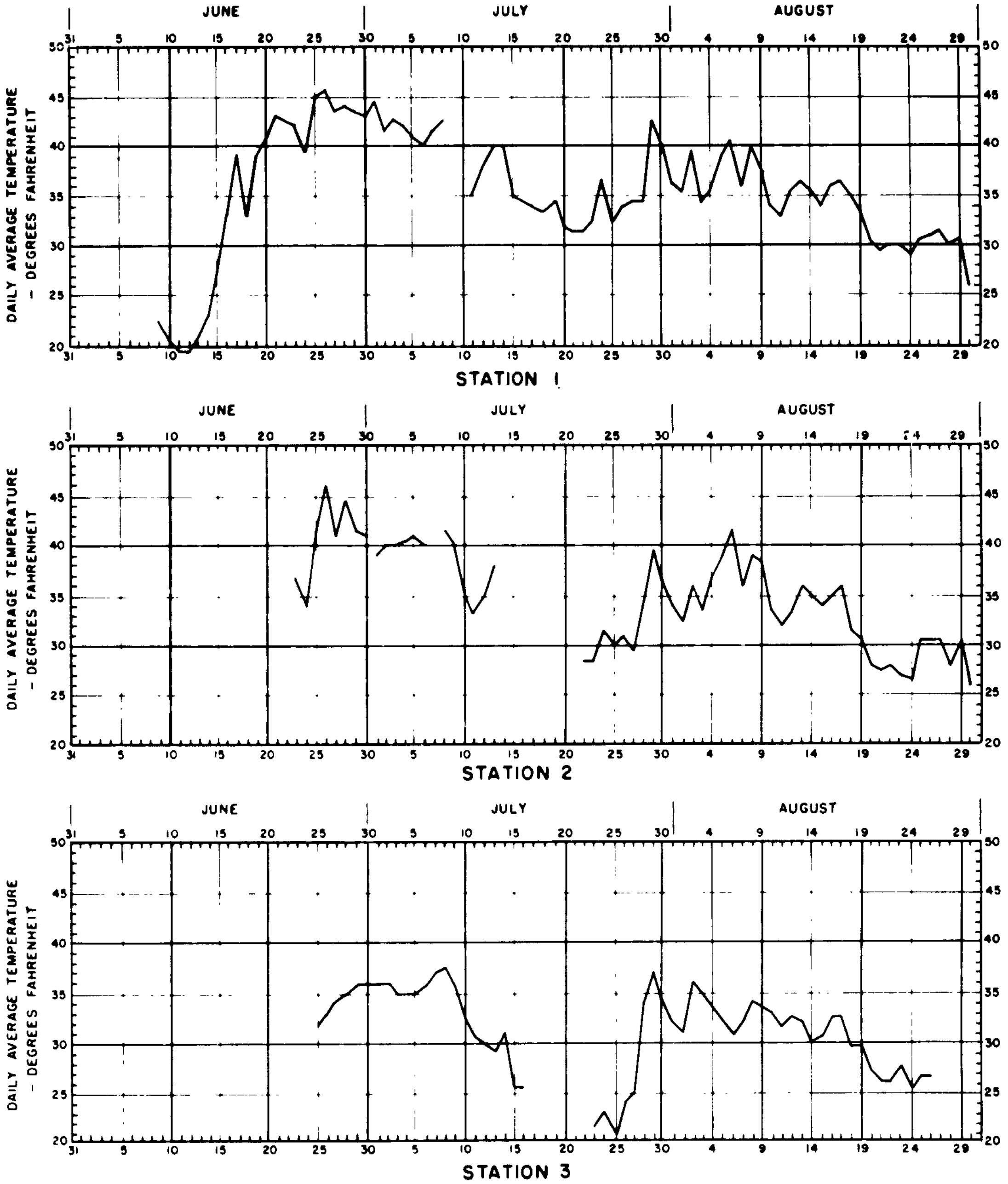


Figure B1. Weather data, Station 1, TUTO, Greenland, 1956.



NOTE: PREPARED FROM DATA FURNISHED BY NATIONAL WEATHER RECORDS CENTER, ASHEVILLE, N C DATA WERE RECORDED BY U S ARMY SIGNAL CORPS METEOROLOGICAL BRANCH.

Figure B2. Air temperature (within standard weather shelter) TUTO, Greenland, 1956.

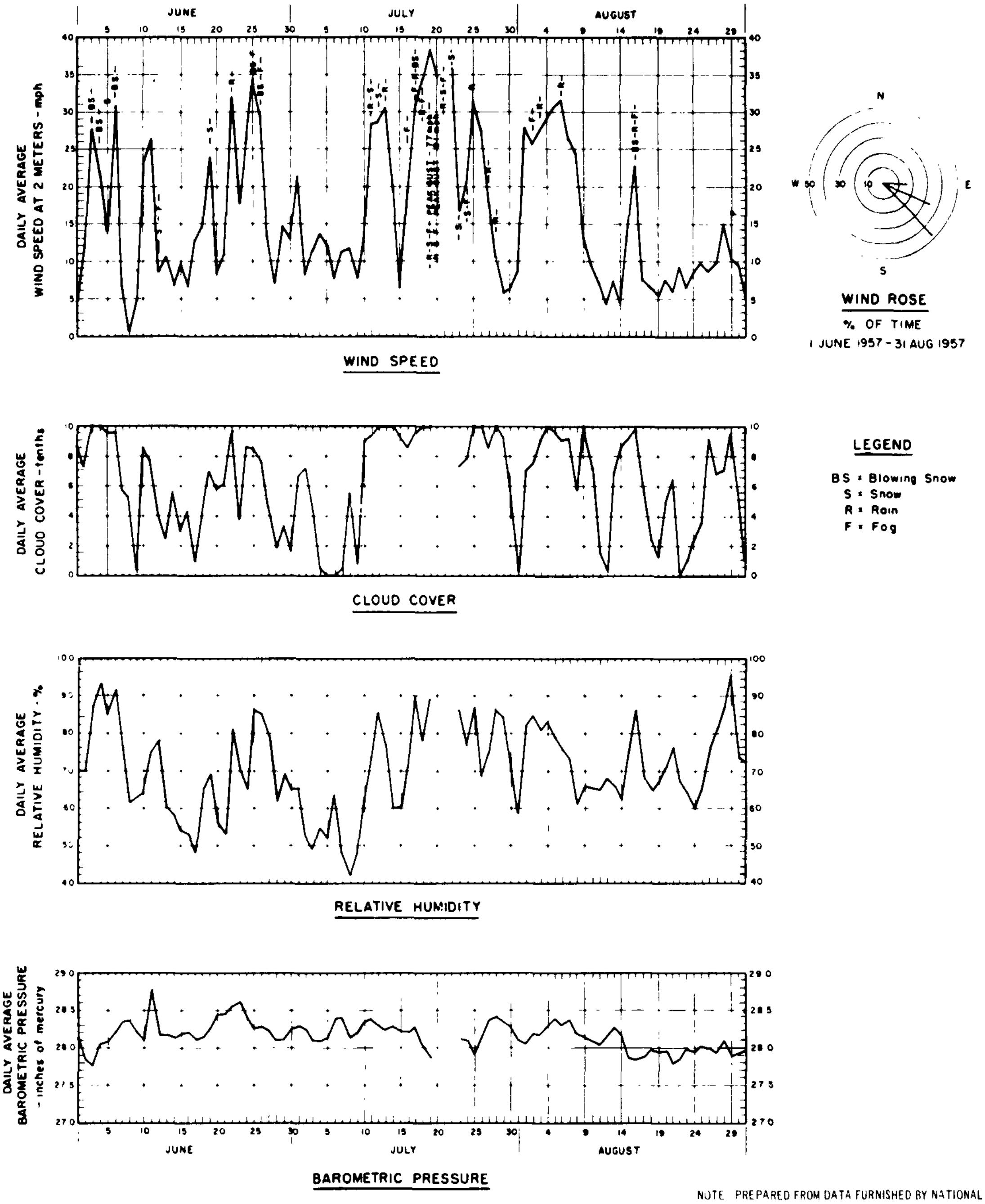
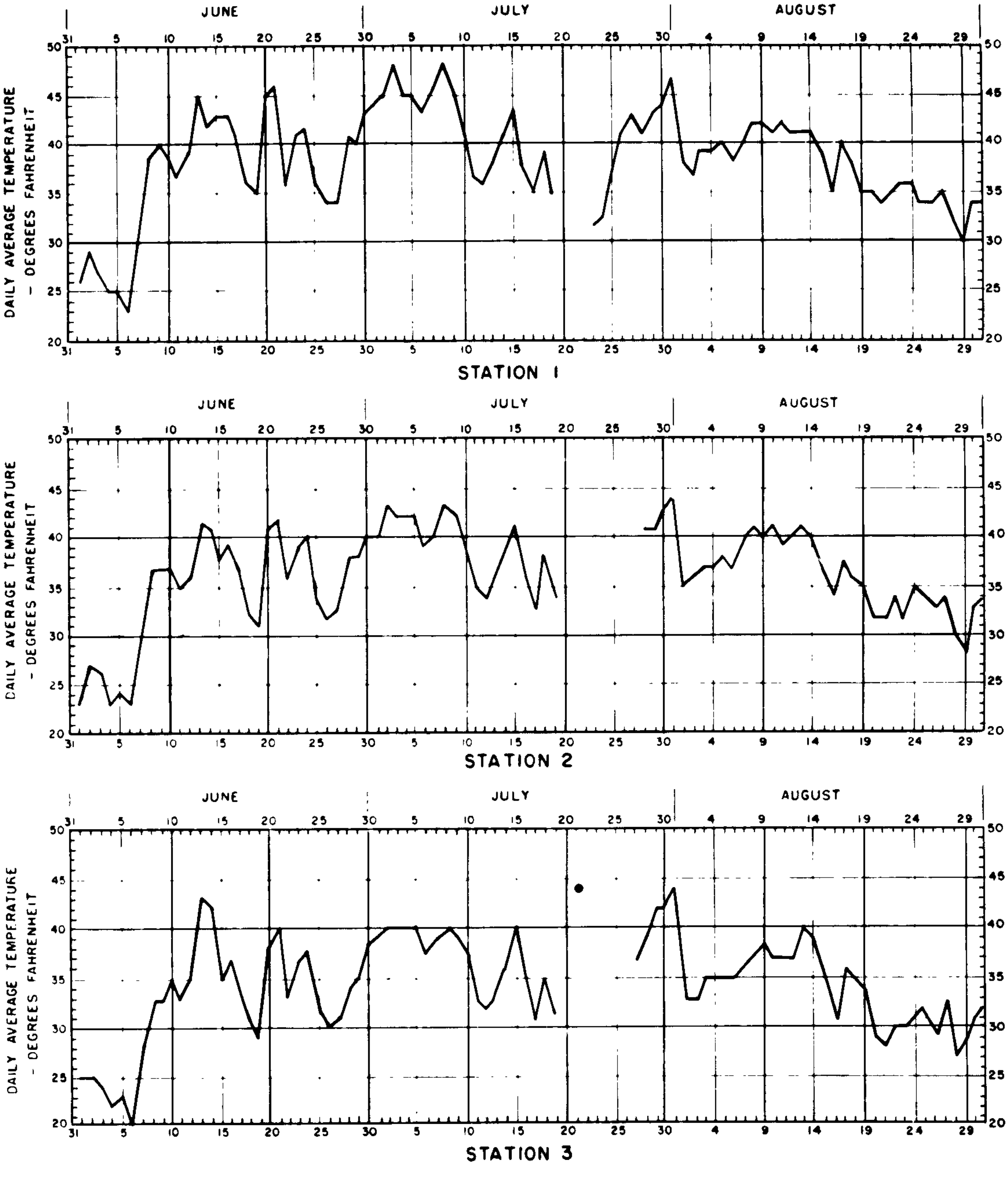


Figure B3. Weather data, Station 1, TUTO, Greenland, 1957.



NOTE: PREPARED FROM DATA FURNISHED BY NATIONAL WEATHER RECORDS CENTER, ASHEVILLE, N. C. DATA WERE RECORDED BY U. S. ARMY SIGNAL CORPS METEOROLOGICAL BRANCH.

Figure B4. Air temperature (within standard weather shelter) TUTO, Greenland, 1957.

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
	12.0	Silty, sandy GRAVEL with cobbles less than 6" diam. Clear, irregular, small masses of ice. Coating of ice on large particles.	GM-II	139.1	7.8
NO PHOTOGRAPH	13.6				
	15.0			144.1	4.3
	16.3	Silty, sandy GRAVEL with cobbles less than 6" diam irregular masses of ice and coatings of ice on large particles.		143.0	6.7
				131.1	9.7
	17.7				

Remarks	(1) Depth ft	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
	17.7	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	140.6	6.7
	19.2	Silty, sandy GRAVEL with cobbles and ice-coated particles. Ice coatings up to 1/4" thick on large cobbles		134.5	8.3
NO PHOTOGRAPH	21.5				
	22.0	BOULDER FRAGMENT			
		Silty, sandy GRAVEL with cobbles less than 6" diam Ice coating on particles	GM-'C	145.2	5.5
		BOULDER FRAGMENT			
	24.8				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs)
- - - - - - Approximate location of sample tested.

NOTES:

(1) *Depths are not to scale because of variation in the scale of photographs*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils," Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, US Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B5. Log of drill hole D5.

(1 of 4 Sheets)

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
	24.8	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	136.2	8.3
Break occurred during core recovery from drill hole.	25.2	BOULDER FRAGMENT			
	25.9	Silty, sandy GRAVEL w/cobbles. Ice coating on particles.	GM-IC		
	26.1	Silty, sandy GRAVEL with cobbles less than 6" diam Ice coating on particles	GM-IC	144.1	6.1
	27.4	Silty SAND with ice coating on particles.	SM-IC	116.1	25.9
Core melted after removal from core barrel.	27.7	Silty, sandy GRAVEL with cobbles less than 6" diam Ice coating on particles.	GM-IC		
	28.1	Silty SAND with ice coating on particles.	SM-IC		
	28.4	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	135.7	7.7
	29.4	Silty, sandy GRAVEL with cobbles and boulders, lenses, and masses of ice. 1/2" thickness, irregularly oriented. Thick coating of ice on large cobble.	GM-II		

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
Boulder Fragments to 8" diam.		Silty, sandy GRAVEL with cobbles and boulders, lenses, and masses of ice. 1/2" thickness, irregularly oriented. Thick coating of ice on large cobbles	GM-II	133.1	8.5
	31.9	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles. Thick coating on larger rocks.	GM-IC	145.9	4.9
	33.3	BOULDER FRAGMENT			
	33.9	Silty, sandy GRAVEL	GM-IC	145.9	4.9
	34.1	BOULDER FRAGMENT			
	34.5	Silty, sandy GRAVEL	GM-IC		
	34.7	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC		
	35.3	BOULDER FRAGMENT			
	36.4	Silty, sandy GRAVEL	GM-IC		
	36.7	BOULDER FRAGMENT			
	37.4		GM-IC		

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs)
- ------ Approximate location of sample tested.

NOTES:

(1) Depths are not to scale because of variation in the scale of photographs.

(2) The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils," Appendix 4, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.

(3) Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.

Figure B5 (Continued)

(2 of 4 Sheets)

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
	37.4	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	137.3	8.0
	38.0	BOULDER FRAGMENT			
	38.4	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles	GM-IC		
	40.0	BOULDER FRAGMENT			
Break occurred during removal from core barrel	40.4	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles	GM-IC	138.2	7.3
	41.9	BOULDER (SANDSTONE)			

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
		BOULDER (SANDSTONE)			
	44.1	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	147.0	5.9
	45.7	BOULDER			
	46.3	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	173.3	5.6
	47.7	Silty, sandy GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC	141.0	7.4

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- - - - - - Approximate location of sample tested.

NOTES.

(1) Depths are not to scale because of variation in the scale of photographs.

(2) The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.

(3) Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.

Figure B5 (Continued)

(3 of 4 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	(2) Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
			Silty, sandy, GRAVEL with cobbles less than 6" diam. Ice coating on particles.	GM-IC		
		52.7				
			Silty, sandy, GRAVEL with cobbles less than 6" diam Ice coating on particles.	GM-IC	143.2	5.6
		55.2				
NO PHOTOGRAPH			Silty, sandy, GRAVEL with cobbles less than 6" diam Ice coating on particles.	GM-IC	138.0	7.7
					143.2	5.6
		55.7				

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	(2) Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
		55.7				
			Silty, sandy, GRAVEL with cobbles less than 6" diam Ice coating on particles	GM-IC	137.9	7.7
			BOULDER FRAGMENT			
				GM-IC		
		62.3	Bottom of Hole			

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs)
- - - - - - Approximate location of sample tested.

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, US Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected*

Figure B5 (Concluded)

(4 of 4 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
Drilled with roller bit (No core)						
Mass of cloudy ice Foliated silt in ice. Elongated bubbles perpendicular to surface. Core melted in barrel Large mass of clear ice		52 6.7	Sandy SILT with irregularly oriented ice lenses, veins, and masses	ML-11	555	705

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
NO PHOTOGRAPH		6.7	Sandy SILT with irregularly oriented ice lenses, veins, and masses	ML-11	49.8	625
Large ice mass with embedded silt particles Large mass of cloudy ice Thin and thick layers of ice finely interbedded with brownish black silt. Fine laminae oriented 60° to the horizon A few pebbles up to 1/2" in diameter End of core not in focus when photographed		7.7	Sandy SILT with stratified ice lenses or layers.	ML-1S		
Core damaged by stone caught in barrel Note verticle ice-filled crack Large mass of clear ice with embedded silt particles and lenses Progressively sandier with coarse sand on bottom Varves not clearly distinguishable above here.		10.3 123	Varves of SAND and SILT with ice lenses or layers	ML-1S	91.6	28.6

LEGEND:

- ——— End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs)
- ------ Approximate location of sample tested.

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 6 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B6. Log of drill hole D6.

(1 of 4 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
Varves and ice lenses are horizontal. Apparent angle is due to camera angle. Core was broken while being removed from barrel. Mass of silt grading into a layer of coarse sand.		142	Varves of SAND and SILT with ice lenses or layers	ML-IS		
Clear ice lens. Within the core traces of vivianite were found. This is a band of this mineral. Ice filled fracture		170	Varves of SAND and SILT with ice lenses or layers	ML-IS	875	308
Crosscutting fracture filled with ice and bounded by horizontal ice bands. Layer of sand.		183	Varves of SAND and SILT with ice lenses or layers	ML-IS		
			Varves of SAND and SILT with ice lenses or layers	ML-IS		

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
Layers of fine sand 1/8" thick. A small amount of coarse sand.		195	Varves of SAND and SILT with ice lenses or layers.	ML-IS	1050	17.5
Core out of focus when photographed.			Varves of SAND and SILT with ice lenses or layers.	ML-IS		
			GNEISS BOULDER			
Sandy gravel lens. Note definite boundary between sandy, gravel lens and alternating layers of fine and coarse sand.		223	Silty, sandy GRAVEL with stratified ice lenses or layers.	GP-GM-IS	128.9	10.6
Sandy gravel lens Note how bedding planes of finer material are affected by the presence of the boulder			Silty, sandy GRAVEL with stratified ice lenses or layers	GP-GM-IS		
Clear ice band. Silty clay lens LL - 235, PI 89, PL = 146. Large ice mass with embedded silt lenses		241	Varves of SAND and SILT with ice lenses or layers	ML-IS		
NO PHOTOGRAPH		252				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- ------ Approximate location of sample tested.

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, US Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B6 (Continued)

(2 of 4 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
Horizontal bands of clear ice Note grading from a silt to a coarse sand. Crosscutting fracture filled with ice and bounded by horizontal ice bands Clear ice band 1" thick Varves and ice lenses are horizontal. Apparent angle is due to camera angle Horizontal bands of clear ice		252	Varves of SAND and SILT with ice lenses or layers	ML-1S	909	285
61 facies changes between 28' and 29' Note crosscutting ice-filled fractures		280	Varves of SAND and SILT with lenses or layers	ML-1S		
End of varved material. Stratified drift begins, progressively less stratified with depth		291	Silty, gravelly SAND with occasional boulders and irregularly oriented lenses, veins, and masses of ice	SP-SM-11		
Atterberg limits were run on most plastic looking material between 25' and 34' LL = 432 PI = 218 PL = 214		298	Silty, gravelly SAND with occasional boulders and irregularly oriented lenses, veins, and masses of ice	SP-SM-11		
Boulder slightly affects bedding of fines above it Mass of ice below bottom of boulder			BOULDER			
Layer of fine material				SP-SM-11		

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens pcf	(3) Mois. Cont. %
Thick coating of ice on cobbles not evident in photographs			Silty, gravelly SAND with occasional boulders and irregularly oriented lenses, veins, and masses of ice.	SP-SM-11	134.0	98
Some melting of core after extraction from barrel. Portion of Gneiss boulder		349	Silty, sandy, GRAVEL with irregularly oriented lenses, veins, and masses of ice	GP-GM-11	1350	101
		376		GP-GM-11		

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- - - - - - Approximate location of sample tested.

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, US Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B6 (Continued)

(3 of 4 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens.	(3) Mois. Cont.
					pcf	%
Some melting of core after extraction from barrel. Note layer of ice above and below cobble. Note vertical ice-filled fracture			Silty, sandy GRAVEL with irregularly oriented lenses, veins, and masses.	GP-GM-II		
		393				
Slight melting of core after extraction from barrel			Gravelly, silty SAND with irregularly oriented lenses, veins, and masses	SM-II	1376	55
		420				
Note ice lens beneath boulder Slight melting of core after extraction from barrel Note ice-filled vertical fracture			Gravelly, silty, SAND with irregularly oriented lenses, veins, and masses	SM-II		
		439				
Note ice-filled fracture				SM-IC		

Remarks		(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens.	(3) Mois. Cont.
					pcf	%
NX bit used from 43.9' to bottom of hole. Core diameter - 1.75". Slight melting of core in barrel.			Gravelly, silty SAND with coatings of ice on particles	SM-IC	140.0	4.6
		46.6	Bottom of hole			

LEGEND:

- —— End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- ------ Approximate location of sample tested.

NOTES:

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils," Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B6 (Concluded)

(4 of 4 Sheets)

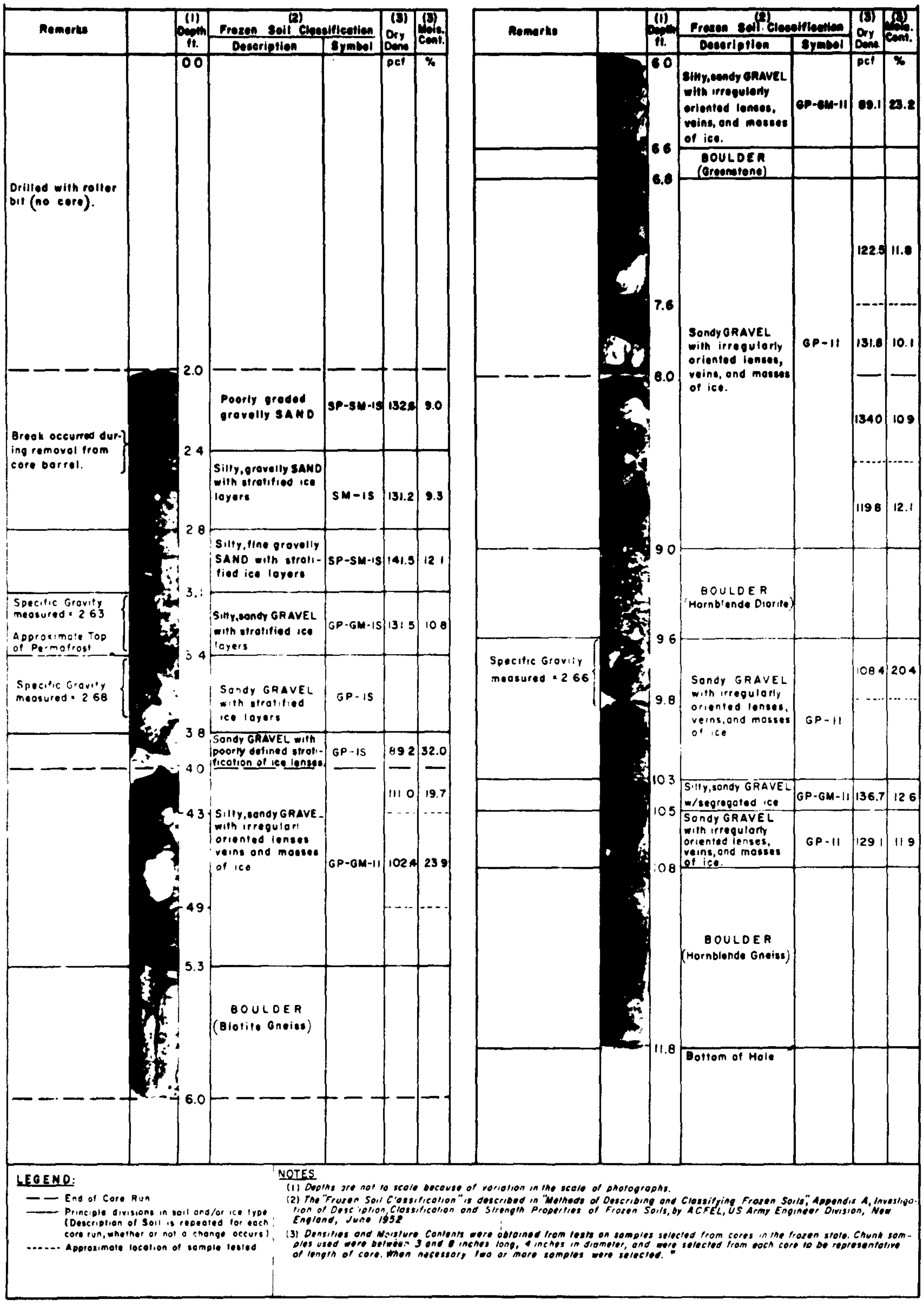


Figure B7. Log of drill hole D8.

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	(2) Symbol	(3) Dry Dens. pcf.	(3) Mois. Cont. %
Roller Bit used from surface to 189.8'; No ice cores were taken.		0.0	ICE			
Cobbles up to 3" in top foot. Traces of vegetation found at 191.5'		189.8	Silty, sandy GRAVEL with cobbles. Ice coating on particles.	SM – IC	128.0	10.4
		193.7				

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	(2) Symbol	(3) Dry Dens. pcf.	(3) Mois. Cont. %
		193.7	Silty, gravelly SAND with ice coatings on particles.	SM – IC	109.2	14.2
Note layer of finer material.		197.6				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- - - - - - Approximate location of sample tested.

NOTES:

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils," Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B8. Log of drill hole D11A.

(1 of 5 Sheets)

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
	200.9	Silty, gravelly SAND with ice coatings on particles	SM-IC	96.6	26.3
In this area the color of the material changed abruptly from brown to dark gray.	205.1	Silty, sandy GRAVEL with ice coatings on particles.	GP-GM-IC	130.4	10.8

Remarks	(1) Depth ft.	(2) Frozen Soil Classification: Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
		BOULDER			
	207.5	Silty GRAVEL with ice coatings on particles.	GM-IC	114.5	16.9
	212.0	CORE NOT RECOVERED			
	212.5				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- ------ Approximate location of sample tested.

NOTES:

(1) Depths are not to scale because of variation in the scale of photographs.

(2) The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.

(3) Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 6 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.

Figure B8 (Continued)

(2 of 5 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens	(3) Mois. Cont.
					pcf.	%
Break occurred during removal from core barrel.		214.5				

Remarks		(1) Depth ft.	(2) Frozen Soil Classification: Description	(2) Frozen Soil Classification: Symbol	(3) Dry Dens	(3) Mois. Cont.
					pcf.	%
			Silty SAND with ice coating on particles.	SM-IC	103.5	22.1
Core melted while the core barrel was being withdrawn from the hole.		220.1				
Note large mass of cloudy ice.		224.8				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- ------ Approximate location of sample tested.

NOTES:

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B8 (Continued)

(3 of 5 Sheets)

Remarks	(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
Note large mass of cloudy ice	224.8				
				66.3	54.1
		Gravelly, silty SAND with ice coatings on particles.	SM - IC		
		Silty, sandy GRAVEL with ice coatings on particles	GP-GM-IC	111.5	18.7
	230.0				
Core melted while the core barrel was being removed from the hole					
		BOULDER			

Remarks	(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
		BOULDER			
Core melted while the core barrel was being removed from the hole					
		BOULDER			
	234.8				
CORE NOT RECOVERED					
	235.8				

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type (Description of Soil is repeated for each core run, whether or not a change occurs.)
- ------ Approximate location of sample tested.

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs.*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils," Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, U.S. Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected.*

Figure B8 (Continued)

(4 of 5 Sheets)

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %
Core melted while the core barrel was being removed from the hole.						
			BOULDER			
			BOULDER			
		2390	Bottom of Hole			

Remarks		(1) Depth ft.	(2) Frozen Soil Classification Description	Symbol	(3) Dry Dens. pcf	(3) Mois. Cont. %

LEGEND:

- — — End of Core Run
- ——— Principle divisions in soil and/or ice type. (Description of Soil is repeated for each core run, whether or not a change occurs)
- - - - - - Approximate location of sample tested

NOTES.

(1) *Depths are not to scale because of variation in the scale of photographs*

(2) *The "Frozen Soil Classification" is described in "Methods of Describing and Classifying Frozen Soils", Appendix A, Investigation of Description, Classification and Strength Properties of Frozen Soils, by ACFEL, US Army Engineer Division, New England, June 1952.*

(3) *Densities and Moisture Contents were obtained from tests on samples selected from cores in the frozen state. Chunk samples used were between 3 and 8 inches long, 4 inches in diameter, and were selected from each core to be representative of length of core. When necessary two or more samples were selected*

Figure B8 (Concluded)

(5 of 5 Sheets)

APPENDIX C: REPORT ON 1957 TUTO RAMP SLOPE INDICATOR MEASUREMENTS

by Stanley D. Wilson*

Introduction

1. In May 1957, the writer was engaged by the U. S. Army Engineer Waterways Experiment Station to assist in obtaining subsurface measurements of the movements of the TUTO ice ramp, utilizing the Wilson slope indicator. This report describes the instruments used and the field installation of observation wells, and presents a detailed analysis of the measurements. Also included are tentative recommendations for continuation of the program.

Instrumentation

2. *Description of the slope indicator.* The complete field instrumentation, as shown in Figure C1, includes the slope indicator, a control box, connecting cable, and plastic casing.

The slope indicator consists of a pendulum that is pivoted on ball bearings and enclosed in a watertight brass cylinder. The cylinder is about 2.5-in. outside diameter and 15 in. long. The tip of the pendulum contacts a precision-wound resistance coil. When that happens, it subdivides the coil into two resistances, forming one-half of a conventional Wheatstone bridge circuit. The other half of the Wheatstone bridge circuit, including switches and batteries, is enclosed in a control box at the ground surface. The inclination of the tiltmeter is proportional to the dial reading of a precision potentiometer in the control box, which reads from zero to 1000. A schematic circuit diagram is shown in Figure C2.

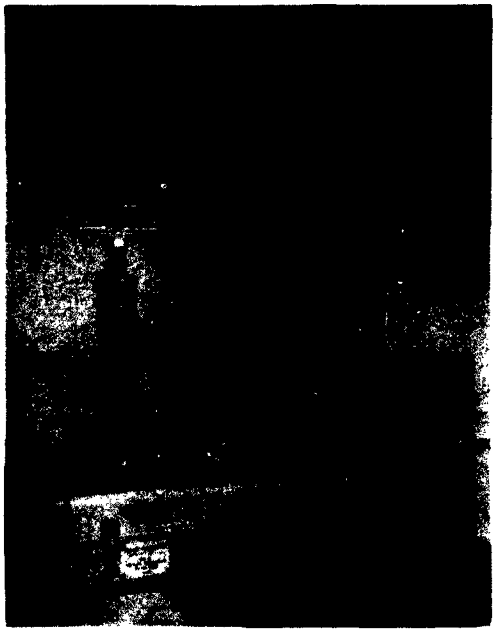


Figure C1. Wilson slope indicator, control box, connecting cable, and plastic casing.

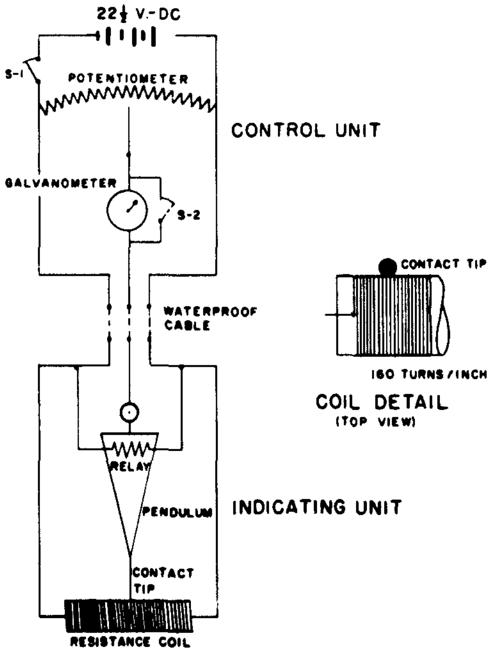


Figure C2. Circuit diagram, Wilson slope indicator.

* Member of the firm, Shannon and Wilson, Soil Mechanics and Foundation Engineers, Seattle, Washington.

When the slope indicator is lowered into the plastic casing observation wells, the guide wheels on each end of the brass cylinder are fitted in the guide slots in the casing. Dial readings are obtained at 5-ft intervals of depth in each of the four slots. The initial position of the casing is readily computed once the inclination (proportional to dial reading) is known. Subsequent readings which show the change in inclination are used to compute the change in position of the casing, i.e. the ice movement. For the particular instrument (No. 107) used in this installation, the relation between change in inclination (ϕ) and dial changes is given by the expression $\tan \phi = \frac{\text{dial change}}{7050}$.

Observation wells

3. In order to measure subsurface ice movements with the slope indicator, observation wells were first installed. The wells consisted of 2-7/8-in. inside diameter, extra heavy wall, plastic well casing lowered into a hole and frozen in place. The casing is extruded in 5-ft lengths and subsequently broached with four longitudinal slots to guide the slope indicator.

Behavior of plastic casing at low temperatures. The Ohio River Division Laboratories, U. S. Army Engineer Division, Ohio River, undertook some rather simple but enlightening tests on the plastic casing to determine its stress-deformation and strength characteristics at -15 F as compared with those at room temperatures. The results showed rather conclusively that these properties were relatively unaffected within this range of temperatures, although actual rupture at the lower temperatures was of a more brittle nature.

Spiral in grooves. The shipment of plastic casing received at TUTO was found to have been broached with a counterclockwise spiral amounting to 1.7 degrees per ft. This was verified by means of a small camera which photographed the orientation of a compass needle at various depths. The results presented herein have been corrected for spiral.

Vertical elongation of casing. Just prior to actual installation of the casing, a review of the then available data indicated that it was probable that some of the planned observation wells would show vertical as well as horizontal components of displacement. Therefore, joints at about 30-ft spacings were left open a fraction of an inch, and a special "gadget" was improvised in the field to measure the vertical elongation or stretch of each of these 30-ft sections. While these measurements were somewhat crude, the results have been of great importance to an analysis of the data presented herein.

Installation of observation wells. Borings were accomplished with a power rotary drill rig, and fairly continuous undisturbed ice cores were obtained. Diesel fuel was used as a drilling fluid to wash out the ice cuttings and to assist in keeping the hole from squeezing inward. The diesel fuel was bailed out of the hole prior to installing the casing. Details of the boring techniques are beyond the scope of this report.

In a normal installation the plastic casing is joined together in 5-ft sections as it is lowered down the drill hole. At TUTO, however, the casing was preassembled into 30-ft lengths in a tent at the campsite. These sections were then hauled to the site by truck, hoisted one at a time with the aid of the drill rig tower, cemented together with the slots aligned, and lowered into the hole. This procedure proved quite satisfactory; the only unfortunate incident occurred in hole D12 when a coupling cracked, allowing 120 ft of tubing to drop to the bottom of the hole. This was salvaged with little damage thereto.

After the casing was lowered into the borehole, antifreeze at a temperature of 15-20 C was poured into the casing, and warm water was poured into the annular space surrounding the casing. Next, a pipe was lowered into the casing, and as the pipe was slowly withdrawn, warm antifreeze

was circulated so that the water would freeze gradually from the bottom to the top of the hole.

Location of observation wells. The following table gives data on the observation wells.

Hole No.	Ramp Road Station	Offset South, ft	Depth of Hole, ft	True Azimuth of East Slot
D11	19+19	549	244*	S73°E
D11B	21+19		25	S16°E
D10A	31+00		25	N88°E
D10	33+00	478	205	S67°E
D10B	35+00		25	S76°E
D12A	64+00		20	S77°E
D12	66+00	700	200	S62°E
D12B	68+00		20	S40°E
D13	74+00	600	40	S46°E
D14	55+00	800	40	S78°E
D15A	**	**	40	S44°E

Note: Locations listed are approximate only.

* This casing was pinched off at depth 95 ft, and subsequently at depth 55 ft.

** Upstream from bridge on Transverse Road.

Slope indicator readings

4. Initial sets of slope indicator readings were obtained shortly after installation of the casings and these were followed at fairly frequent intervals by additional sets. Dates of initial readings for the various casings are listed below:

Hole No.	Date of Readings	Hole No.	Date of Readings
D11	14 June	D12	17 June
D11B	8 June	D12B	10 June
D10A	8 June	D13	10 June
D10	20 May	D14	8 June
D10B	8 June	D15A	3 July
D12A	10 June		

During the period 23-26 August, all casings were surveyed with the slope indicator, at which time the tubes were filled with antifreeze, sealed, and capped for the winter.

Results of slope indicator measurements

5. *General.* Each set of data requires lengthy analysis and evaluation. In hole D10, for example, there have been nine sets of data, each set consisting of 160 individual readings. Each pair of readings has been corrected by graphical procedures to account for the spiraling in the slots. Further, the relative movements within the depth of the casing have been smaller than anticipated, and it has been necessary to pay particular attention to all possible inaccuracies in measurements. Records of all data are not included in this report since detailed presentation of all supporting data is not justified.

Method of correction for spiral. It has previously been explained that the slots in the plastic casing spiraled in a counterclockwise rotation of 1.7 degrees per ft. The graphical procedure used to correct this is shown in Figure C3. The particular example chosen is from 144-ft depth in hole D10. The following data were obtained in the field:

Date	Difference in Dial Readings		Date	Difference in Dial Readings	
	N-S	E-W		N-S	E-W
20 May 1957	-160	+29	Changes:		
2 July 1957	-168	+38	20 May-2 July	-8	+9
26 Aug 1957	-182	+50	20 May-20 Aug	-22	+21

The true bearing of the E slot at the top of the casing is S67°E. The N-S and E-W dial changes are first plotted (Fig. C3). These have developed as listed above, referenced to the slot bearings at the top of the casing. At 144-ft depth, however, the slots have rotated 245 degrees counterclockwise. To avoid replotting the data, the true reference bearings are rotated. The projection of the two points on the E-W reference line can be determined graphically as being -12 and -30 dial units, respectively. By repeating this procedure at each successive depth, the true E-W component of dial change can be obtained. These corrected values have been used in the figures at the end of the report.

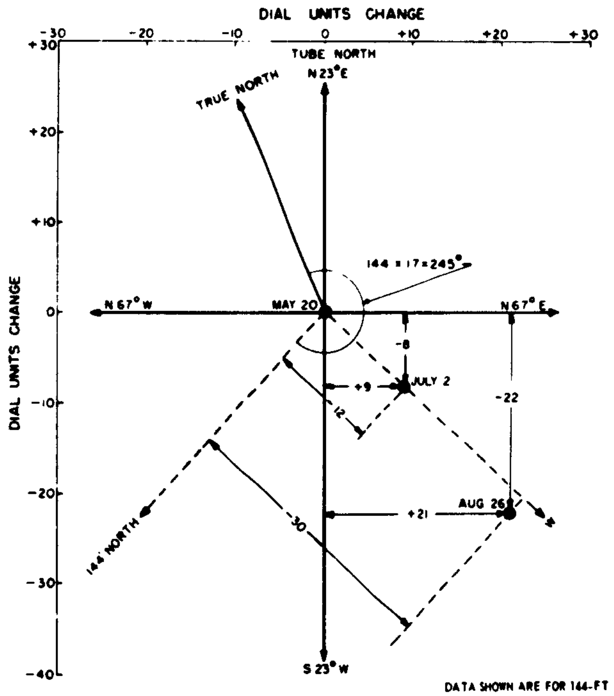


Figure C3. Graphical procedure for spiral correction.

In Figure C4 are plotted the two components of dial changes at each depth for the above intervals of time. The first interval changes (42 days) have been indicated as open circles, the total interval changes (96 days) as solid circles. The lines connecting the points represent changes from 2 July to 26 August (54 days). These components have been corrected for spiral and represent true bearings. The numbers beside the points represent depths.

In studying this plot, it will be noted that the trend of changes is E-W, although there is considerable N-S scatter as well. The scatter is such as to not make it possible to pinpoint the exact direction of movement. Based on surface evidence of movement, it has been assumed that all such movement is in a westerly direction. In Figure C5 are plotted the E-W component of dial changes, derived directly from Figure C4. This is a plot of dial change (or change in inclination) with depth. Note the excellent agreement between the two sets of data, and the orderly increase in change in inclination with time. In contrast, the N-W component (not plotted) showed erratic scatter and no cumulative trend of displacements. The scatter tends to increase with depth.

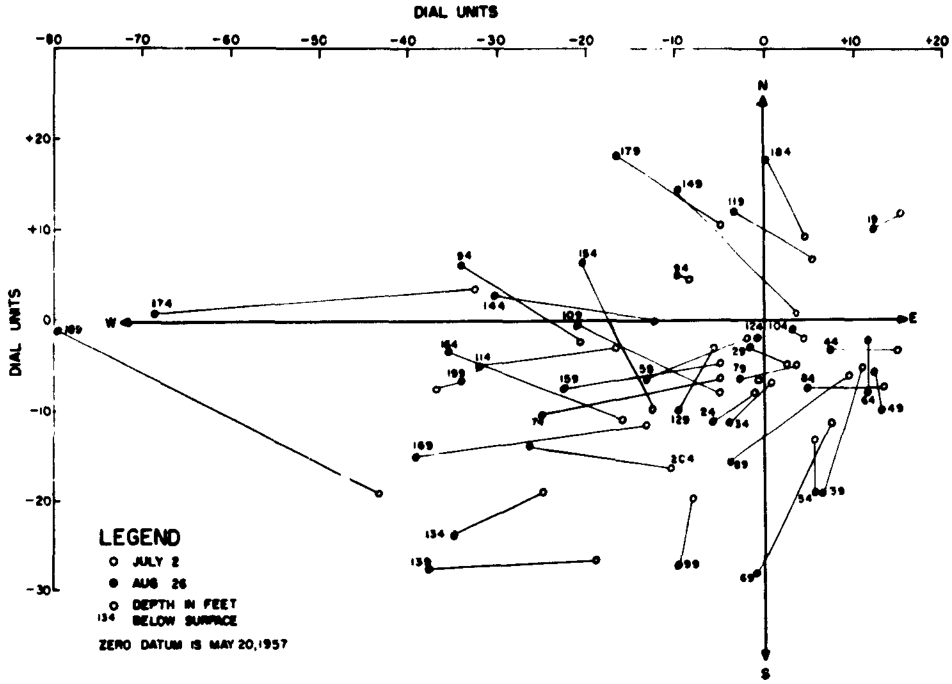


Figure C4. Dial changes, hole D10.

There are two probable reasons for this large scatter. First, the casing may not have been completely frozen in the ice because of antifreeze leakage and contamination with diesel fuel. Secondly, and probably the main reason, the plastic casing was elongated at the same time the horizontal movements developed. Thus, the deeper readings have been taken each time at a different depth. The total stretch has been of the order of 8 in., which means that, near the bottom of the casing, the original set of dial readings is being compared with the final set of readings which were obtained 8 in. higher in the casing. At depths where the individual sections were slightly curved when installed, a change in position of the slope indicator results in an apparent change in inclination; that change is not the result of horizontal shear displacements.

In Figure C5 are plotted the E-W changes in dial units for each 5-ft increment of depth. The deflections (or movements) which were computed from this data are shown on the left of Figure C6. The agreement between the data of 2 July and 16 August (and of the intermediate data not presented herein) is very good and is an indication that the data are reliable.

The data presented in Figures C5 and C6 show conclusively that the shear displacement of the casing has been cyclic in character, with maximum shear at the center of layers about 20 to 30 ft in thickness. However, it is not conclusively established that this is representative of the shear deformation of the ice mass. Since appreciable quantities of antifreeze leaked through the joints and into the annular space surrounding the casing, it is possible (although not too probable) that the casing has not frozen rigidly to the ice, and that there have been cyclic displacements of the casing within the confines of the borehole (the N-S scatter, although cyclic, is much more erratic and not as progressive as for the E-W component). Final resolution of this question may have to await further field measurements with the slope indicator.

The vertical elongation of the casing in D10 was likewise measured at periodic intervals. These measurements consisted of measuring the distance from the top of the casing to successive joints in the casing. The equipment was improvised in the field and consisted of a spring-loaded

lever at the tip, a pipe weight, a connection from the tip to a 100-ft steel tape, another connection, and a second 100-ft steel tape. Unfortunately, the connections were not always of the same length, resulting in minor inaccuracies. The first set, on 23 May, was very carefully executed, as were the final sets on 13 August and 26 August, the latter two being accomplished with a 200-ft steel tape. As a matter of record, all field data are presented in the following tabulation. The elongations between 20 May and 13 August are plotted on the right half of Figure C6.

(Note: There is a possibility that the measured elongation in the lower 25 ft is too great due to loosening of the lower plug. This error might amount to as much as 1 to 2 in.)

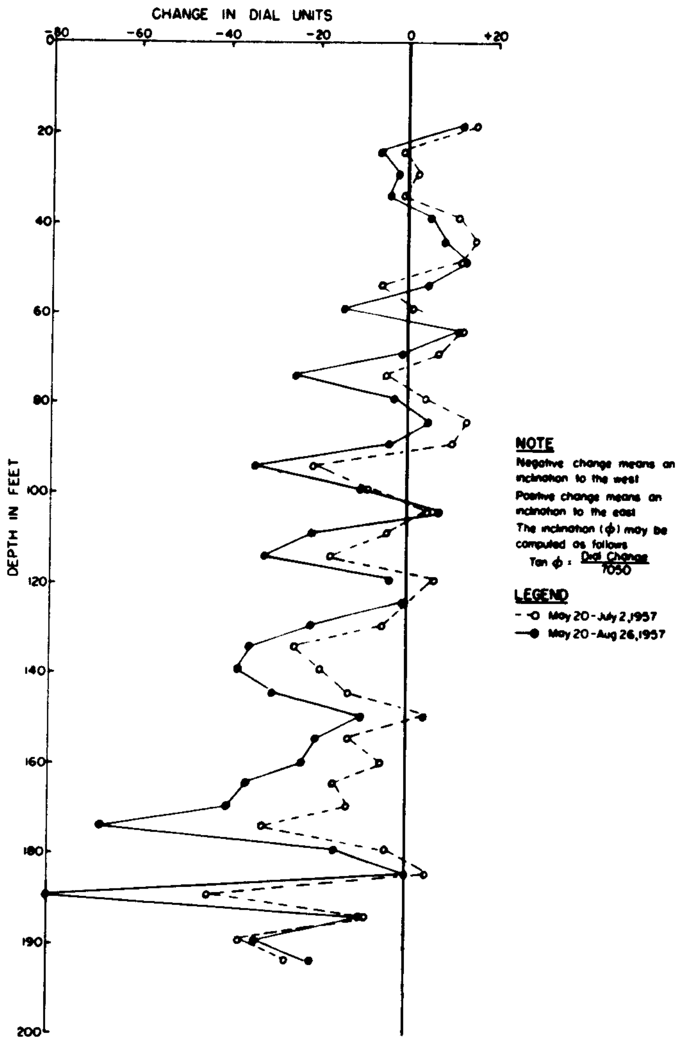


Figure C5. E-W component of dial changes, hole D10.

Elongation in Hole D10

Measured Depths to Joints from Top of Casing, ft

23 May	27 May	17 June	2 July	11 July	13 Aug	26 Aug
			11.70			
16.71	16.78				16.77	
26.79		26.74	26.89	26.92	26.85	26.91
31.80	31.86		31.91	31.92	31.85	
36.82						
46.86		46.80	46.96	47.01		
87.05	87.65	87.04	87.21	87.25	87.24	87.31
117.13		117.18	117.31	117.34		117.85
147.28		147.33	147.40		147.63	
			172.55			
177.41	177.51	177.49		177.73	177.84	
207.47	207.65	207.60	207.74	207.94	208.16	

Hole D11. The casing in hole D11 was originally installed through the ice cap and into the permafrost to a total depth of 245 ft. During the freezing, it was pinched off at a depth of 97.6 ft. Subsequently, it was found that the slope indicator would not go below 54 ft in the N-S slots; therefore, the data are limited to the upper 54 ft.

In Figure C7 are shown the two-dimensional dial changes, corrected for spiral, for the intervals 14 June to 29 July and 14 June to 24 August 1957. As with D10, there is a consistent E-W trend with some scatter in the N-S component. Figure C8 shows the E-W dial changes versus depth, and also the deflections computed from the above data.

(Note: The initial readings were obtained on 8 June 1957. However, it is believed that the casing was not completely stabilized by freezing on that date, and therefore, the data of 14 June have been taken as a zero reference.)

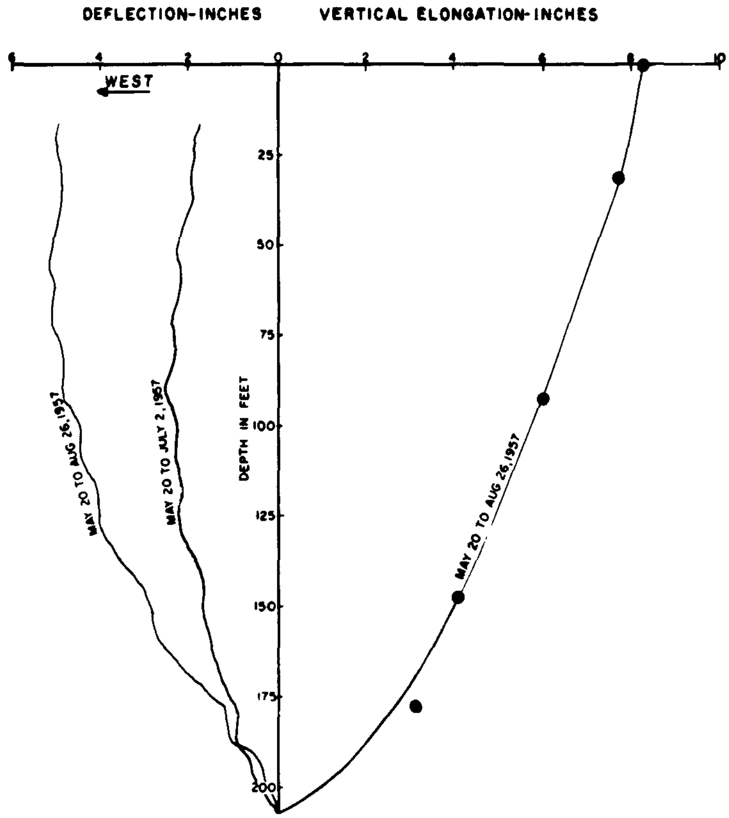


Figure C6. Deflection and elongation, hole D10.

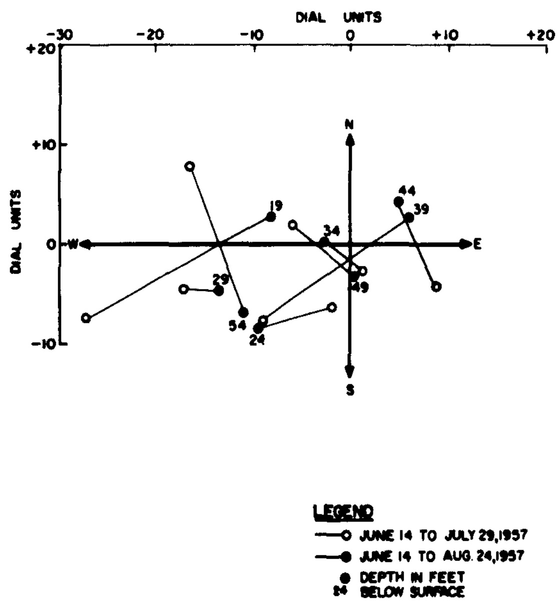


Figure C7. Dial changes, hole D11.

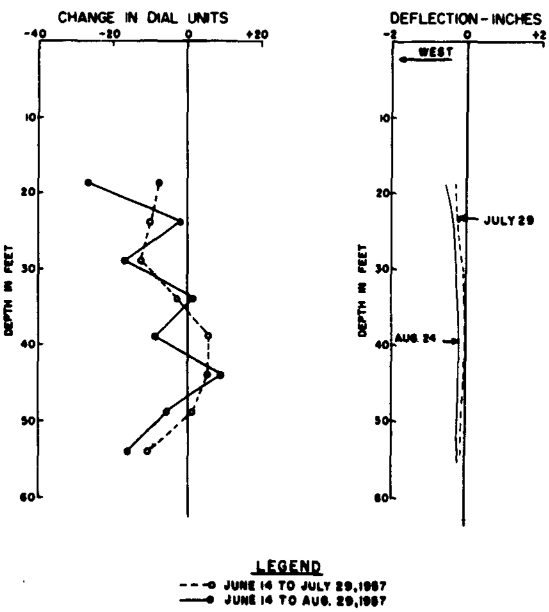


Figure C8. E-W component of dial changes and deflections, hole D11.

The deflections shown in Figure C8 appear to exhibit the anticipated trend and direction; however, they are so small as to be within the range of instrument inaccuracies.

Hole D12. The casing in hole D12 was dropped during installation and subsequently ice formed inside the casing and had to be thawed out. The data from this hole have tended to be more erratic than from other holes. In Figure C9 are plotted the two-dimensional dial changes that developed between the dates of 17 June and 23 August. Note the symmetrical distribution of the changes about both the N-S and E-W axes.

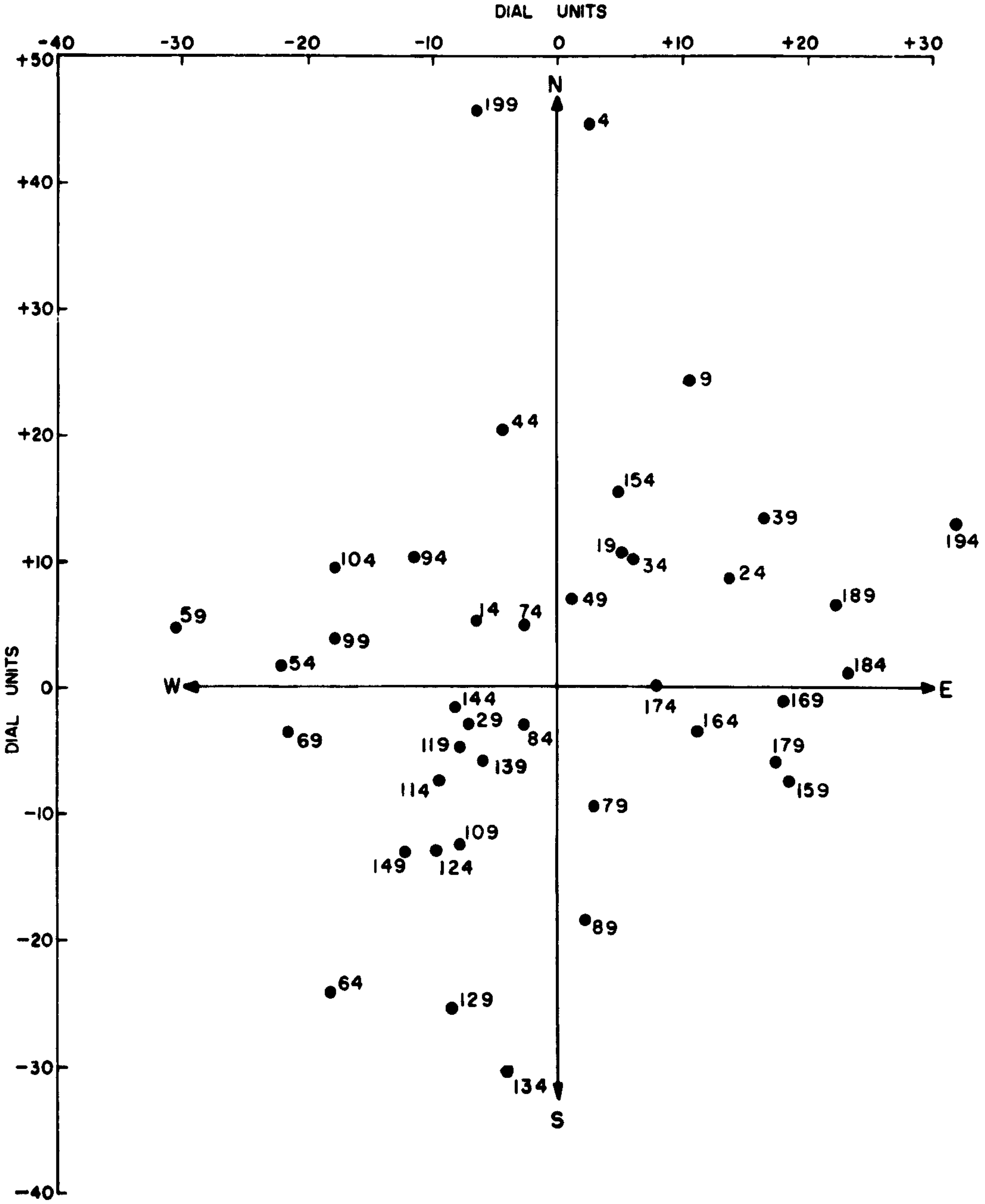


Figure C9. Dial changes, D12, 17 June to 23 Aug 1957.

In Figure C10 are plotted the true E-W component of dial changes for the periods 17 June to 29 July and 17 June to 23 August. Note the larger changes which developed in the first period as compared with the changes which developed in the second period. It is believed that the casing was not fully frozen, and that the first set of data represent readjustments of the casing within the borehole.

In Figure C11 are plotted the computed E-W movements for the same two periods shown in Figure C10. The indicated movements for the first period are partly in the wrong direction and of such an order of magnitude that they could well be shifting within the borehole. There are no apparent movements for the second period. From this it is concluded that there have been no relative horizontal movements within the depth of the boring.

Vertical elongation measurements, similar to those made on D10, were attempted and found subject to the same errors. The pertinent field data are summarized in the tabulation below.

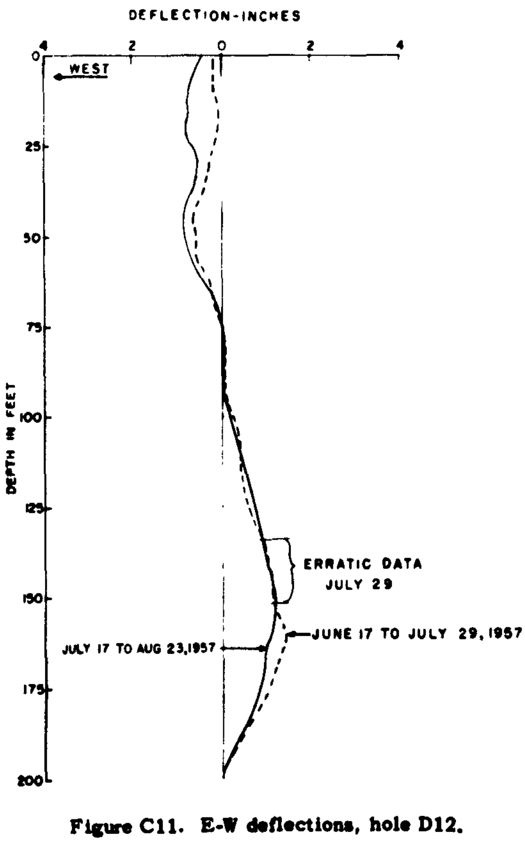


Figure C11. E-W deflections, hole D12.

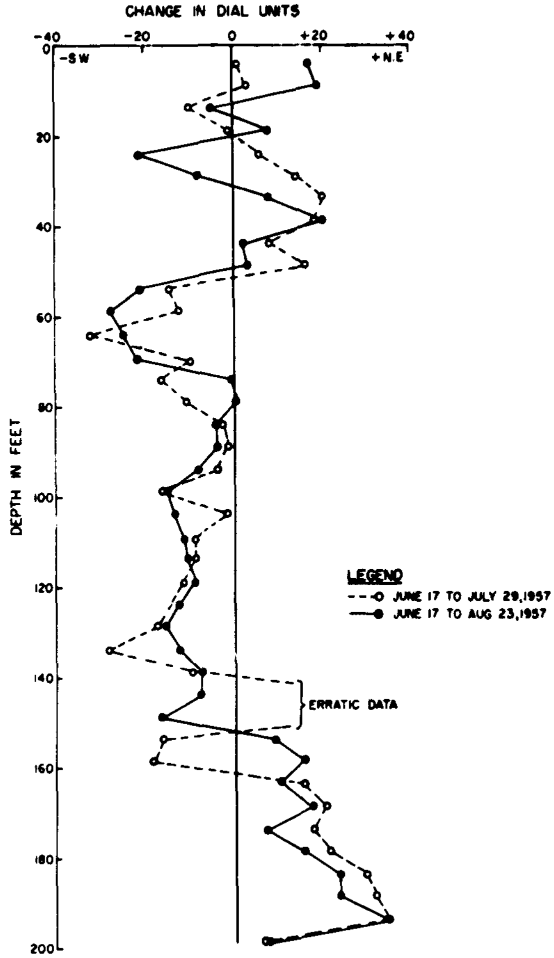


Figure C10. E-W component of dial changes, hole D12.

The data below indicate no elongation in the lower 165 ft. It is probable that the small measured elongation in the upper 35 ft is the result of inaccuracies in the tape connections.

Elongation in Hole D12

Measured Depths to Joints from Top of Casing, ft

17 June	2 July	13 Aug	24 Aug
3.00			
	14.72		
24.58			
34.66	34.72	34.82	34.81
	63.92		
68.81		68.97	
108.31	108.40	108.51	108.46
141.03		141.22	141.14
171.13			
200.11	200.18	200.34	200.24

Holes D10A, D10B, D11B, D12A, D12B, D13, D14, and D15A. All these holes are from 25 to 40 ft in depth. The upper 5 to 15 ft have in most instances been affected by surface melting. Elongation measurements were not undertaken.

Figures C12 and C13 show the two-dimensional dial changes which developed between the date of installation and the final set of readings in late August. The variations are random and show no orientation of direction. The intermediate readings (not plotted) showed similar scatter. E-W dial changes or computed deflections have not been plotted since the data do not warrant this.

With the exception of hole D15A, all the above-listed holes are adjacent to or in the vicinity of holes D10, D11, and D12. Since analysis of these latter holes shows no measurable differential horizontal movements within the upper 50 ft, it is not surprising that none of these shallow holes show any evidence of horizontal shear movement.

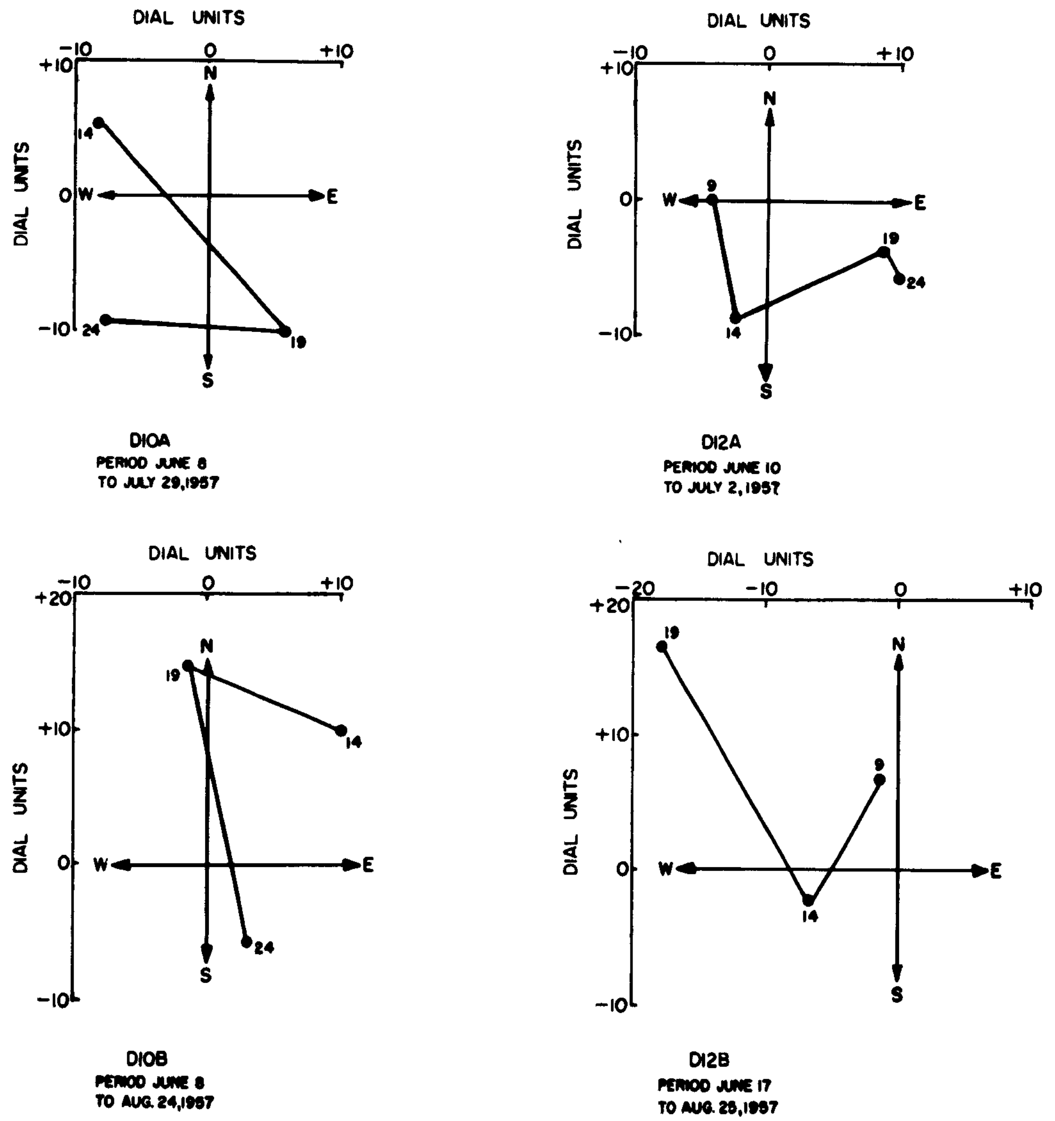


Figure C12. Dial changes, D10A, D10B, D12A, and D12B.

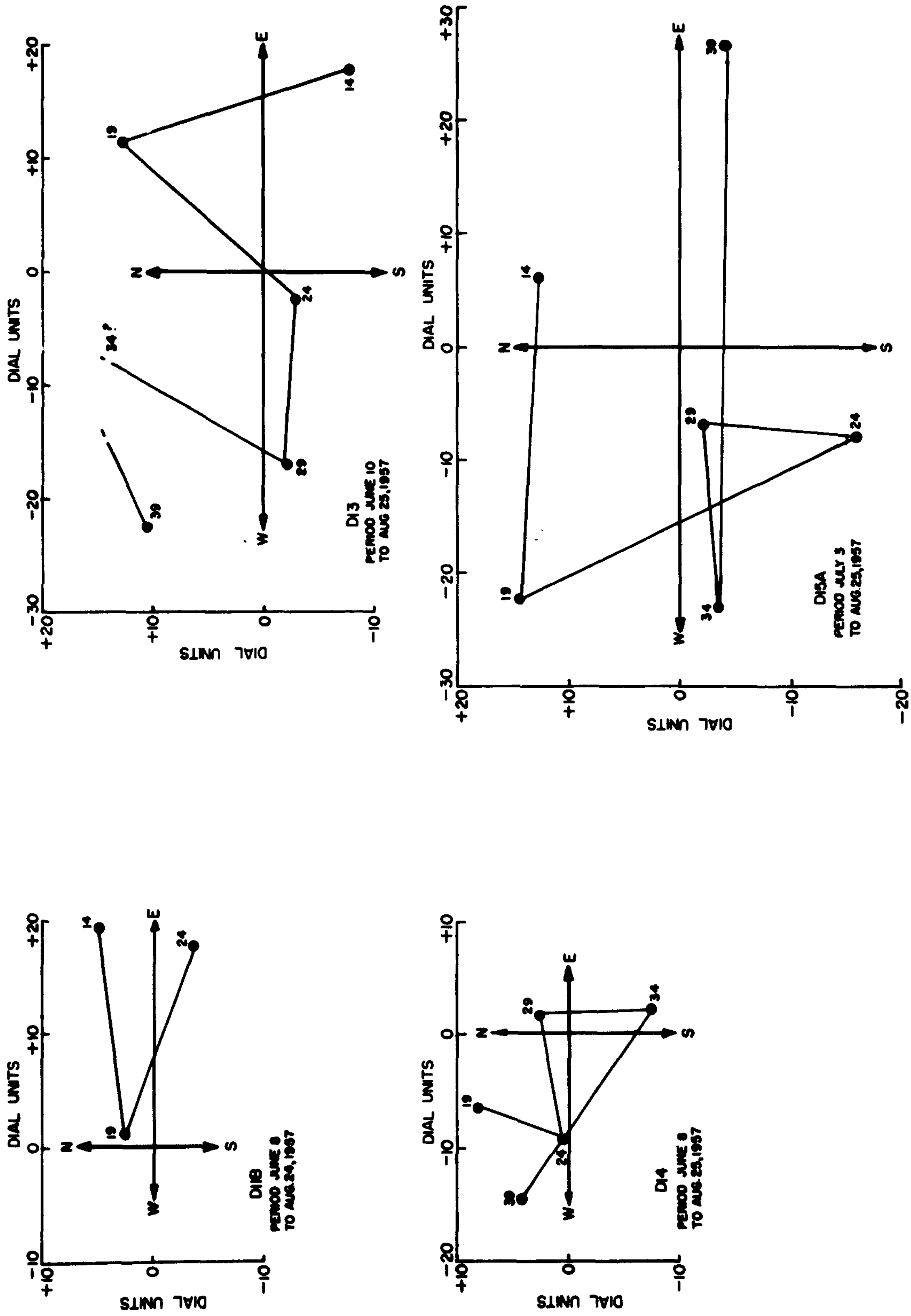


Figure C13. Dial changes, D11B, D13, D14, and D15A.

Discussion of ice movements

6. Of the three deep casings, D10, D11, and D12, only D10 showed measurable differential horizontal movements within the depth of the casing. In contrast, triangulation data from 20 June to 20 August 1957 showed much greater surface velocities, as tabulated below:

Hole No.	60-Day Total Surface Movement	90-Day Differential Movement
D10	1.03 ft = 6 in./month	5 in. = 1.67 in./month
D11	Zero	Zero
D12	2.01 ft = 12 in./month	Zero

In Figure C14(c) is plotted the observed surface movements at five stations on the ramp for the period August 1956 to August 1957. At D10 the rate is seen to be nearly 8 in. per month (slightly larger than that listed above) and at D12 movement is 12 in. per month, the same as listed above. Considering possible errors of such measurements, the agreement is considered excellent.

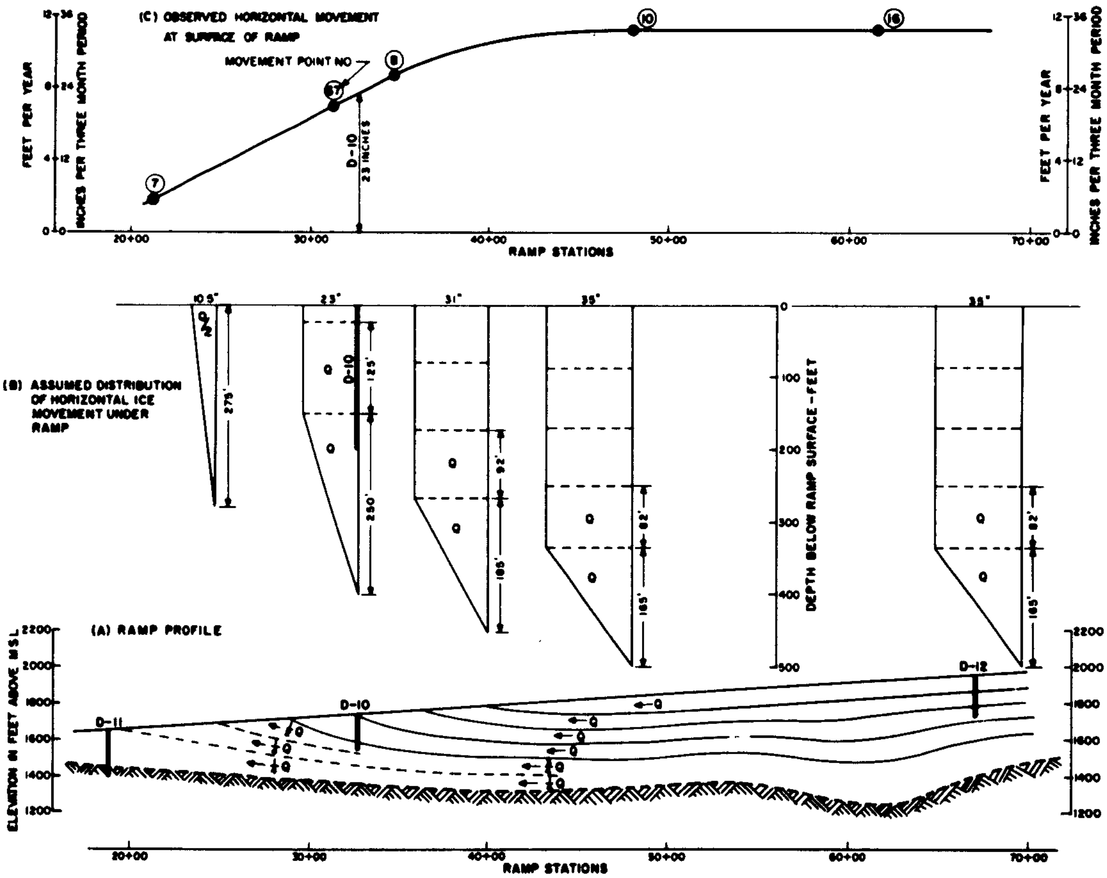


Figure C14. Analysis of ice movements.

In Figure C15 on the left is plotted the total horizontal movement at D10, taken from the curve in Figure C14(c). Starting at the top are superimposed the measured differential horizontal movements from Figure C6 for the three-month period from 20 May to 20 August 1957. A reasonable extrapolation of the curve projects to zero velocity at the lower boundary of the ice.

Figure C14(a) shows a section of the ice ramp to true scale as obtained from seismic surveys in 1957. Directly above hole D10 is shown an approximation of the movement curve of Figure C15. Assuming zero velocity at the lower ice boundary and a linear increase of velocity above, the distribution of horizontal ice movements at selected stations along the ramp is also shown. Each of these graphs has been subdivided into zones so that equal volumes (Q) of ice flow past a vertical section of each zone in a given time. If these basic assumptions are reasonably correct, then the zone boundaries represent flow lines of ice movement. These flow lines have been constructed within the ice ramp profile shown in Figure C14(a). The lowermost flow line represents the boundary between shear deformations below and constant velocity (across a given section) above. Note that the flow lines do not represent shear planes or planes of sliding.

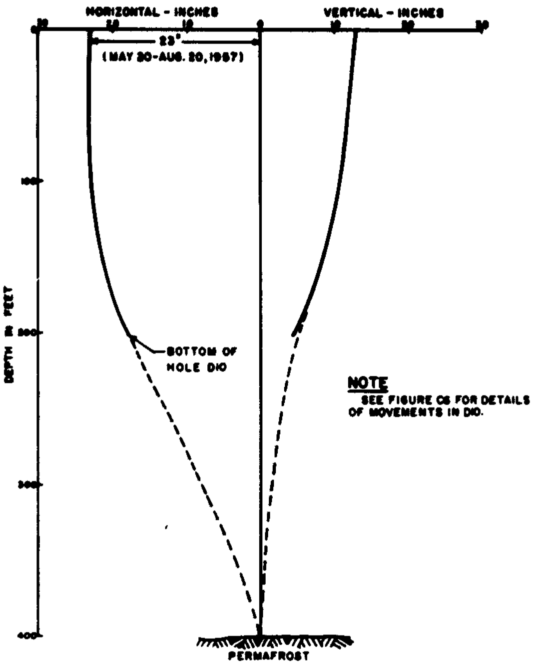


Figure C15. Estimated total movements, hole D10.

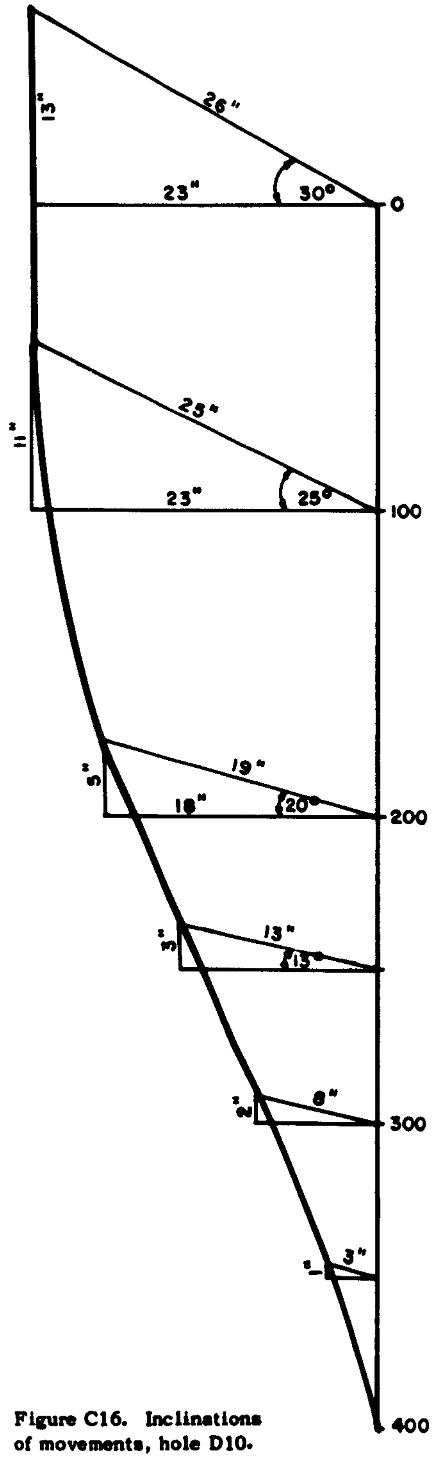


Figure C16. Inclinations of movements, hole D10.

The flow line which intersects the ice surface near the top of D10 is inclined at an approximate angle of 30 degrees to the horizontal. In Figure C16 is plotted this inclination which, together with the total horizontal displacement of 23 in. from Figure C14, gives a vertical movement of 13 in. On the right of Figure C15 is plotted this vertical movement, and superimposed thereon is the measured elongation from Figure C6. This curve has likewise been extrapolated to zero at the base of the ice ramp, and the data were used to complete the curve of Figure C16.

The movement profile shown in Figure C14(a) now fits all the available data pertaining to surface

and subsurface movements, although the 30-degree inclination of movement at D10 is subject to verification and possible modification.

In Figure C17 the surface movements which would result in a given period of time, if there were no ablation, are plotted to a convenient scale. The length of each arrow represents, to this scale, the horizontal component of velocity as shown in Figure C14(c). The inclination is obtained from Figure C14(a). Note the hump which is developed in the vicinity of D10 (opposite the hump in the Ramp Road). While other factors may contribute to the ice hummocks observed in this vicinity, the flow pattern shown in Figure C14 must be the prime factor.

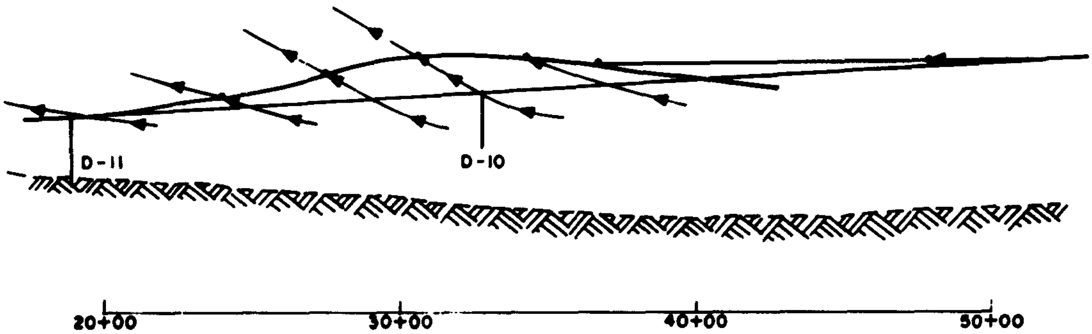


Figure C17. Computed surface movements, TUTO Ramp.

Recommendations for additional investigations

7. The measurements should be repeated in all of the holes at the beginning of the 1958 season. This will be of particular interest in the three deep holes and in some of the intermediate-depth holes. In D10, the elongation should first be measured, and the depths corrected so that all readings will be taken at positions in the plastic casing corresponding to the original positions.

If additional casings are to be installed, they should be installed in each case through the ice and into the permafrost. This may require several installations of approximately 500 ft in depth. In connection with any proposed future installations, it is hoped that some of the problems encountered with last years installations can be avoided. It is now possible to obtain casing with precision-cut grooves which do not spiral, and improved couplings of aluminum have been developed. Techniques for lowering casings to any desired depth, without danger of dropping the entire length, have been developed, and improved electrical conducting cable is being developed.

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U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss. APPROACH ROADS, GREENLAND 1956-1957 PROGRAM, by H. W. Stevens. April 1963, ix, 105 pp and 3 appendices - illus - tables. (Technical Report No. 3-505, Report 2)

Unclassified report

The report describes progress during the summers of 1956-1957 on development of methods, techniques, and criteria for constructing roads on glacial ice surfaces and adjacent ice-free terrain. Terrain, weather, ice movement, ice ablation, meltwater flow, performance of road fills, subsurface temperatures, and thaw penetration were studied. Soil properties and physiography of an area about 15 miles square near Camp TUTO were investigated to obtain data on sources of borrow materials and other data needed in design of roads, building foundations, etc. Road construction was primarily a continuation of that begun previously, with the objectives of making existing roads more useful and investigating several proposed designs. An 80-ft-long, wooden-pile-bent bridge was constructed on the ice by 6 men in 2-1/2 weeks; it supported the heaviest mobile equipment used and performed satisfactorily for 1-1/2 thaw seasons. Appendices A and B present supplementary data on personnel, equipment, weather, borings, and ice surface measurements. Appendix C, by Mr. S. D. Wilson, describes use of the Wilson Slope Indicator at TUTO.

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2. Ice
3. Roads
4. Polar regions

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